Measurement of minimum ignition energy in hydrogen-oxygen-nitrogen premixed gas by spark discharge

Ayumi Kumamoto¹, Hiroto Iseki¹, Ryo Ono¹, Tetsuji Oda²
¹Department of Advanced Energy, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8561, Japan
²Department of Electrical Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

E-Mail: kumamoto@streamer.t.u-tokyo.ac.jp, ryo-ono@k.u-tokyo.ac.jp and oda@ee.t.u-tokyo.ac.jp

Abstract. We have measured the minimum ignition energy (MIE) of hydrogen-oxygen-nitrogen premixed gas by spark discharge. The gap distance of point-point electrode was changed between 0.3 and 1.0 mm. The effects of hydrogen and oxygen concentrations on the MIE were measured. It was 0.006 mJ for H₂ with O₂ / (O₂+N₂) = 0.35 mixture, while it was 0.017 mJ for H₂ with dry air mixture. For H₂–O₂ mixture, it was below 0.004 mJ, which was not precisely measured due to the limitation of our measurement.

1. Introduction
Hydrogen generates power by reaction with oxygen. It is clean and a promising energy source without the exhaust of carbon dioxide. We can reduce the dependence on fossil fuel by using hydrogen energy. Hydrogen is sensitive to electrostatic discharge (ESD) compared with other inflammable gases. The minimum ignition energy (MIE) of a hydrogen–air mixture is only 0.019 mJ, whereas that of other flammable gases such as petrol, methane, ethane, propane, butane, and benzene is usually on the order of 0.1 mJ according to Lewis and von Elbe [1]. Therefore, the assessment of the electrostatic hazard for hydrogen is urgent because hydrogen is used in fuel cells and fuel cell vehicles. However, the assessment has not yet been sufficiently achieved.

MIE is an important parameter in the assessment of electrostatic hazard. It has been measured for various flammable gases including hydrogen [1]. MIE is usually measured using capacitive spark discharge whose electrical circuit is shown in Fig. 1, because the capacitive spark is the most frequent electrostatic ignition source in practice. The capacitor C is charged up to voltage V, then the charge stored in the capacitor is discharged in a test chamber filled with an explosive mixture. MIE is defined as the lowest discharge energy required for ignition, where the discharge energy is defined as CV²/2 [1]. In this study, we measure the MIE of hydrogen–oxygen–nitrogen premixed gas using the capacitive spark discharge.
2. Experiment

Hydrogen–oxygen–nitrogen premixed gas is ignited in a 110 mL stainless chamber. Hydrogen, oxygen, and nitrogen are introduced up to a total pressure of 1 atm (100 kPa) in the chamber. The concentration of each gas is determined from their partial pressures, which are measured with a Baratron vacuum gauge (MKS Instruments, Model 626A). The chamber has a safety cap with 4 cm diameter as shown in Fig. 2. When an explosion occurs, it releases the explosion energy.

The spark discharge occurs between needle-to-needle electrodes placed in the center of the chamber. The needles are made from tungsten, and have a 1 mm diameter and a 40° tip angle. The gap distance can be adjusted with a micrometer. MIE is measured using the capacitive spark discharge and compared with literature values [1-2]. Fig. 1 shows the electrical circuit for generating the capacitive spark. $C_c$ is the capacitance of the ceramic capacitor connected in parallel to the spark gap and $C_e$ is the capacitance of the electrode. The charge stored in the capacitor $C = C_c + C_e$ is discharged at the spark gap. $C_c$ is measured with an LCR meter (Kokuyo, KC-536). It is provided to cover the range from 0.67 to 470 pF.

The HV power supply is connected to the spark gap through a cable and a high-resistance $R_p = 1 \text{ G}\Omega$. The voltage of the HV power supply, $V_p$, increases from 0 to 5.5 kV at a low rate of increase (i.e., 0.1 kV/s). As $V_p$ increases, the capacitor voltage $V_c$ increases with a time constant of $CR_p$. When $V_c$ exceeds the breakdown voltage of the spark gap, a discharge occurs at the spark gap. The resistance $R_p$ is chosen so that the charging time constant becomes $CR_p > 4 \text{ ms}$, which is much longer than the spark duration (< 100 ns). Therefore, almost no charge stored in the stray capacitance of the power supply cable flows into the spark gap during discharge, thus the stray capacitance of the cable has no influence on the discharge. When a discharge occurs, the HV power supply detects the spark noise and sends trigger signals to the HV power supply and oscilloscope for synchronization. Upon receiving the trigger signal, the HV power supply reduces its output to 0 V within 0.5 ms to prevent the occurrence of subsequent sparks.

The spark voltage, $V_s$, is obtained from $V_c$ just before the occurrence of the spark. However, the measurement of $V_c$ with a high-voltage probe is undesirable because the input impedance of the probe affects the discharge. In the present experiment, $V_c = V_p$ is applicable because the increasing rate of $V_p$ is sufficiently low. Therefore, $V_s$ can be obtained from $V_p (= V_c)$ just before the occurrence of the spark. $V_p$ is monitored with an oscilloscope (Tektronix, TDS3034B, 300 MHz) after being reduced by a factor of 10,000 with a voltage divider. The discharge energy is defined as $CV_s^2 / 2$, which can be changed by varying $C$ and $V_s$. 

![Figure 1. Electrical circuits for capacitive spark circuit.](image1)

![Figure 2. Safety cap on chamber.](image2)
C\textsubscript{e} is determined using the relation \( (C_e + C_c)V_s = \int I(t)dt \), where \( I(t) \) is the discharge current, assuming that the electrical charge in \( C \) is almost completely discharged by the spark discharge. \( I(t) \) is measured using a 2.3 \( \Omega \) carbon resistor connected in series between the capacitor \( C \) and the spark gap. The voltage drop of the 2.3 \( \Omega \) resistor is measured with the oscilloscope. \( C_e \) is determined to be 1.7\text{pF} with an error of 10\% when it is measured using various \( C_c \) between 0-3.3\text{pF}. The above assumption that the electrical charge in \( C \) is almost completely discharged by the spark discharge is proved as follows.

We measured \( C_e \) of an almost identical electrode in another larger chamber (1 L) using the relation \( (C_e + C_c)V_s = \int I(t)dt \). Under a fixed voltage of \( V_s = 3.6 \text{ kV} \), \( C_e \) was determined to be 1.8\text{pF} with an error of 10\% when various \( C_c \) between 5-100\text{pF} were used. Next, \( C_e \) was measured using the LCR meter which also gave a value of 1.8\text{pF}. This agreement verifies that almost all the electrical charge in \( C_e + C_c \) was discharged. In the present chamber (110 mL) used for the MIE measurement, \( C_e \) cannot be measured using the LCR meter because the volume of the chamber is too small to insert the probe of the LCR meter. However, we consider that the electrical charge in \( C_e \) is almost completely discharged by the spark discharge because (i) it is true at least in the larger chamber and (ii) the estimated \( C_e \) of the present chamber (1.7\text{pF}) is in agreement with that measured using the larger chamber (1.8\text{pF}) within an error of 10\%. Therefore, we use \( C_e = 1.7 \text{ pF} \). The error of \( C_e \) is estimated to be 10\%.

3. Results and discussion
The MIE of the hydrogen-oxygen-nitrogen premixed gas is measured using the capacitive spark. The procedure for determining the MIE is as follows. First, the ratio of \( O_2 / (O_2+N_2) = 0.35 \), which is the equivalent ratio to the experiment of MIE by Lewis and von Elbe [1]. MIE depends strongly on the gap distance between the electrodes [1, 2]. First, it was fixed to 0.5 mm. According to our previous work [2], the minimum of MIE of hydrogen–air mixture is obtained at 20-30\% hydrogen
concentration with 0.5 mm gap distance. Then the gap distance was changed between 0.3 and 1.0 mm. The results are shown in Fig. 3 for gap distances of 0.3 mm, 0.5 mm, 0.7 mm, and 1.0 mm for various hydrogen concentrations. Then, the minimum of these resultant curves are taken as the MIE for each hydrogen concentration. The MIE determined using this procedure is plotted in Fig. 4. It reaches a minimum of 0.0057 mJ at a hydrogen concentration of 30%. The MIE is also measured for hydrogen with \( \text{O}_2 / (\text{O}_2 + \text{N}_2) = 1.00 \) mixture. It means hydrogen-oxygen premixed gas without nitrogen. This is plotted in Fig. 4, where the MIE obtained in this work is compared with those of previous studies [1, 2]. In this work, our experimental setup has a lower limitation of 0.004 mJ because our setup has a minimum capacitance \( C_e \). Therefore, we could not measure the MIE for 20-65% hydrogen concentration with \( \text{O}_2 / (\text{O}_2 + \text{N}_2) = 1.00 \).

The MIE obtained in this work is in good agreement with previous values. The differences are probably caused by differences in the configuration and material of the electrodes. These factors generally cause differences in MIE within a factor of 2-3 [3].

Fig. 3 shows that the minimum of MIE for \( \text{O}_2 / (\text{O}_2 + \text{N}_2) = 0.35 \) is obtained at \( \text{H}_2 \) concentration of 30%. The effect of gap distance in this mixture is measured in detail. Fig. 5 shows the result. The minimum of MIE is obtained at around 0.4-0.5 mm gap distance.

**Figure 5.** MIE of \( \text{H}_2\text{-O}_2\text{-N}_2 \) compounding ratio was fixed \( \text{O}_2 / (\text{O}_2 + \text{N}_2) = 0.35 \); for each gas concentration was \( \text{H}_2 \) 30%, \( \text{O}_2 \) 24.5%, \( \text{N}_2 \) 45.5%.

### 4. Conclusions

The MIE in hydrogen-oxygen-nitrogen premixed gases of \( \text{O}_2 / (\text{O}_2 + \text{N}_2) = 0.35 \) and 1.00 was measured using a capacitive spark discharge. The minimum of MIE was 0.006 mJ for \( \text{H}_2 \) with \( \text{O}_2 / (\text{O}_2 + \text{N}_2) = 0.35 \) mixture, and below 0.004 mJ for \( \text{H}_2 \) with \( \text{O}_2 / (\text{O}_2 + \text{N}_2) = 1.00 \) (\( \text{H}_2 \) - \( \text{O}_2 \) mixture). The latter value could not be measured because it is much lower than the lowest possible spark energy of our experimental setup (0.004 mJ), which was determined by \( C_e = 1.7 \) pF and the minimum spark voltage \( V_s = 2.2 \) kV. We need lower \( C_e \) and \( V_s \) than the present experiment to measure the minimum of MIE \( \text{H}_2 \) - \( \text{O}_2 \) mixture.

### References

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