Spark ignition of hydrogen-air mixture

Ryo Ono1 and Tetsuji Oda2

1High Temperature Plasma Center, The University of Tokyo,
5-1-5 Kashiwanoha, Kashiwa, Chiba, 227-8568, Japan
2Department of Electrical Engineering, The University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan
ryo@streamer.t.u-tokyo.ac.jp

Abstract. The electrostatic ignition of hydrogen-air mixture is investigated. First, the
minimum ignition energy (MIE) of the hydrogen-air mixture is measured using a capacitance
spark discharge. The influences of the spark gap length, humidity, and the spark pulse duration
on the MIE are studied. It is shown that the MIE is approximately constant when the relative
humidity increases from 0% to 90% at room temperature, and that the MIE is approximately
constant when the spark duration is varied from 5 ns to 1 ms. Next, the density of OH radicals
and gas temperature in an incipient spark-ignited hydrogen(50%)-air flame are measured using
laser-induced predissociation fluorescence (LIPF). The time evolutions of the OH density and
the gas temperature are measured from 3 µs to 200 µs after ignition.

1. Introduction
Hydrogen is a promising fuel which can be used for fuel cells. It is expected to replace oil and natural
gas for most uses, including transportation fuel. However, for developing the hydrogen-based energy
system, the electrostatic hazard for hydrogen should be assessed because of its high sensitivity to
electrostatic discharge (ESD). The minimum ignition energy (MIE) of a hydrogen-air mixture is below
0.02 mJ, whereas that of other flammable gases such as methane, ethane, propane, butane, and
benzene is usually higher than 0.2 mJ [1]. For investigating the electrostatic ignition of hydrogen, we
measure (i) the MIE of hydrogen-air mixture using a capacitance spark discharge and (ii) density of
OH radicals and gas temperature in the incipient spark-ignited hydrogen-air flame using laser-induced
predissociation fluorescence (LIPF) with a tunable KrF excimer laser.

2. Experiment
A hydrogen-air mixture is ignited in a 1 L stainless chamber. The chamber is evacuated to below
5×10³ atm (0.5 kPa), then hydrogen and dry air are introduced up to a total pressure of 1 atm (100 kPa).
The hydrogen concentration is determined from the partial pressures of hydrogen and air, which are
measured with a Baratron vacuum gauge. The chamber is sealed with aluminum foil of 3 cm diameter.
When an explosion occurs, the aluminum foil ruptures to release 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. Figure 1 shows the electrical circuit for generating the
spark discharge. \( C_c \) 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 capacitance $C = C_c + C_e$ is discharged at the spark gap. The capacitances are measured with an LCR meter (Kokuyo, KC-536). $C_e$ is 1.8 pF and $C_c$ is provided to cover the range from 2.5 pF to 470 pF.

The HV power supply is connected to the spark gap through a cable and a high-resistor $R = 1 \text{ G}\Omega$. 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 $CR$. When $V_c$ exceeds the breakdown voltage of the spark gap, a discharge occurs at the spark gap. The resistance $R$ is chosen so that the charging time constant becomes $CR > 4 \text{ ms}$, which is much longer than the spark duration ($< 100 \text{ ns}$). Therefore, almost no charge stored in the stray capacitance of the power supply cable flows into the spark gap during discharge. When the discharge occurs, the pulse generator detects the spark noise and sends trigger signals $S_{\text{trig}}$ to the HV power supply, the oscilloscope, and the laser for synchronization. Upon receiving the $S_{\text{trig}}$ 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, $V_c \approx V_p$ is applicable because the increasing rate of $V_p$ is sufficiently low. Therefore, $V_c$ can be obtained from $V_p$ just before the occurrence of the spark. The discharge energy is defined as $CV_s^2/2$, which can be changed by varying $C$ and $V_s$.

Figure 2 shows typical current profiles for a 0.5-mm-gap spark measured with a current probe (Pearson, Model-2877, 200 MHz). The values of the spark energy and the capacitance $C$ are also given in the legend of the figure.

For LIPF measurement, a tunable KrF excimer laser with a 30-ns pulse width is used for exciting OH radicals [2]. The laser wavelength is tunable within a range of 247.8 to 248.7 nm with a spectral bandwidth of approximately 3 pm. The KrF laser excites vibrationally ground-state OH radicals ($X^2\Pi, \nu" = 0$) to ($A^2\Sigma^+, \nu' = 3$) state. Three branches, $P_2(8), Q_1(11)$, and $O_1(6)$, are excited. The fluorescence from the excited OH radicals is measured with a photomultiplier tube (PMT) through an interference
filter (297 ± 5 nm), which is optimized to transmit the OH fluorescence from the \((\text{A}^3\Sigma^+, \nu' = 3) \rightarrow (\text{X}^2\Pi, \nu'' = 0)\) band. When two-dimensional LIPF technique is used for measuring the spatial distribution of OH density, an ICCD camera (ORIEL InstaSpec V) is used instead of the PMT for detecting the OH fluorescence.

![Figure 2. Current profiles of 0.5-mm-gap spark.](image)

### 3. Results and discussion

#### 3.1. MIE of hydrogen-air mixture

Figure 3 shows the MIE of hydrogen-dry air mixture. It takes a minimum of 0.017 mJ at a hydrogen concentration of around 22 to 26%. The MIE obtained in this work is in good agreement with those of previous studies [1, 3, 4]; only small differences (a factor of 2) are observed. The differences are probably caused by differences in the configuration and material of electrode. These factors generally cause differences in MIE within a factor of 2 to 3 [3-5]. In Fig. 3, the MIE for a 2 mm gap is approximately constant for hydrogen concentrations between 10% and 50%, and it shows a sudden increase when hydrogen concentration decreases to less than 10%. Such an abrupt increase at approximately 10% is also seen for 1 and 3 mm gaps. It suggests that the hydrogen ignition is strongly suppressed below a concentration of 10%.

The effect of humidity on the MIE is measured. The hydrogen-humid air mixture is prepared by mixing humid air of 90% relative humidity with “dry” hydrogen. Therefore, the humidity of the mixture is, for example, 45% when the hydrogen concentration is 50%. The result shows that the increase in humidity from 0% to 90% leads to only a slight increase in the MIE (several tens percent) and no marked influence of humidity is observed. This indicates that humidity has no significant influence on the MIE of hydrogen-air mixtures.

Figure 4 shows the MIE of H2(22%)-dry air mixture as a function of spark duration. The spark duration is varied by connecting a series resistance between the capacitance and the spark gap. The result shows that the MIE is approximately constant within 5 ns to 1 ms spark duration.
Figure 3. MIE of hydrogen-dry air mixture (solid line) and that at fixed gap distances (broken lines).

Figure 4. MIE of H\(_2\)(22\%)-dry air mixture by RC series spark.

3.2. LIPF of OH radicals
Density of OH radicals and gas temperature are measured by LIPF for H\(_2\)(50\%)-air mixture. The gap distance is fixed to 2 mm. Figure 5 shows the growth of the incipient flame ignited by \(E = 3E_{\text{min}}\), where \(E\) is the spark energy and \(E_{\text{min}} = 0.075\) mJ. This result gives the volume of the flame which is required for determining the OH density.

Figures 6 and 7 show the time evolutions of OH density and OH rotational temperature (= kinetic temperature) of the incipient flame for \(E = 1.35E_{\text{min}}\) and \(0.95E_{\text{min}}\). The mixture is ignited for \(E = 1.35E_{\text{min}}\) and not ignited for \(E = 0.95E_{\text{min}}\). These density and temperature are average in the flame. The
spatial distribution of these parameters cannot be measured due to the low sensitivity of this LIPF measurement.

![Figure 5. Two-dimensional LIPF of OH radicals. The LIPF signal intensity is normalized for each image.](image)

The reaction in hydrogen-air flame proceeds via [1]:
\[
\begin{align*}
O + H_2 & \rightarrow OH + H, \\
H + O_2 & \rightarrow OH + O, \\
OH + H_2 & \rightarrow H_2O + H.
\end{align*}
\]
This chain-branching process is exothermic. It generates heat and additional O, H, and OH radicals as it proceeds. Figure 7 shows the temperature increase by the heat of the reaction. In our incipient flame, the number of OH radicals increases after ignition. The decrease of OH density in Fig. 6 is due to the increase in the volume of the incipient flame, which exceeds the increase of the number of OH radicals.

4. Conclusions
The MIE of hydrogen-air mixture was measured and the influences of the spark gap length, humidity, and the spark pulse duration on the MIE were studied. It was shown that the MIE takes a minimum of 0.017 mJ when the hydrogen concentration is 22 to 26%, and that the humidity and the spark duration have no marked influence on the MIE.

For investigating the ignition process of the hydrogen-air flame, the density of OH radicals and gas temperature were measured by LIPF using a tunable KrF excimer laser. It showed that the decrease in OH density, the increase in the number of OH radicals in the flame, and the increase in gas temperature after the ignition of the mixture in order of \(\mu s\).

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Figure 6. Time evolution of OH density after ignition of H$_2$(50%)-air mixture.

Figure 7. Time evolution of OH rotational temperature after ignition of H$_2$(50%)-air mixture.