Numerical study on the spark ignition characteristics of hydrogen-air mixture using detailed chemical kinetics
(Effects of energy supply procedure and spark channel radius on MIE)

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Hydrogen is a promising fuel and is expected to replace hydrocarbon fuels for its significant potentials to reduce the pollutants and greenhouse gases. It is very important to investigate minimum ignition energy (MIE) on safety standards and ignition process of hydrogen-air mixtures. In this study, the spark ignition of hydrogen-air mixture is investigated by using detailed chemical kinetics and considering the heat loss to the electrode. The purpose of this study is emphasized in the effects of the energy supply procedure and the radius of the spark channel on the MIE.

Key Words: Spark Ignition, Hydrogen-Air Mixture, Minimum Ignition Energy, Detailed Chemical Kinetics

1. Introduction
Hydrogen is a promising fuel that could replace hydrocarbon fuels due to its potential to reduce pollutants and greenhouse gases. In particular, easily applicable utilization of hydrogen is in the SI engine as a pure fuel and fuel blends to start the flame propagation for the near-zero engine-out emission and high flame speed. The latter is unique to hydrogen and able to ignite premixed mixture at low equivalence ratios to achieve high thermal efficiency.

The minimum ignition energy (MIE) is the minimum amount of energy required to ignite a combustible vapor, gas, or dust cloud due to an electrostatic discharge. MIE is an important parameter for judging the ignition ability of combustion systems, and is considered to be an important safety criterion for combustible gases. Because the MIE of hydrogen-air mixture is very small, it is easy to accidentally give rise to a disaster by spark ignition. Even though some experimental researches have been performed on hydrogen–air mixtures to determine the MIE for the spark ignition and the flame kernel development process, the details of the ignition mechanism have not been satisfactorily explained. Numerical simulation is a convenient method for studying the specific effects of any factor on the spark ignition characteristics and for calculating important physical and chemical properties such as the instantaneous high temperature and the heat release rate, which are difficult to obtain experimentally.

In this study, the spark ignition of a hydrogen–air mixture was investigated using detailed chemical kinetics and considering heat loss to the electrode. The purpose of this study was to analyze the effects of the energy supply procedure and spark channel radius on the MIE.

2. Analytical model and numerical methods
Two-dimensional cylindrical coordinates were used to calculate the ignition processes (Fig. 1). The distance between the first 60 grid points around the electrode was set at 0.025 mm due to the smaller quenching distance of a hydrogen–air mixture compared to a methane–air mixture in the r and z directions. The computational region spanned 5.8 mm in both the r and z directions. The r and z axes were located on lines of symmetry for all variables. The other two boundaries were treated as outside boundaries. The radius of electrode R and the electrode gap distance L were set 0.3 and 0.5 mm, respectively. The electrode surface temperature was set to 300 K.

Fig. 1 Analytical model with electrode and boundary conditions for a hydrogen–air mixture

The initially quiescent mixture of hydrogen and air in the computational domain had an equivalence ratio $\phi-1$ and an initial temperature of 300 K and was at atmospheric pressure. The numerical method was the same as that used in the previous studies for methane–air mixtures. GRI-mech 3.0 was applied to the chemical kinetics model. The finite volume method was used to discretize the governing differential equations. The spark duration $t_s$ and the time step were chosen to be 20 and 1 $\mu$s, respectively. The semi-implicit method for pressure-linked equations (SIMPLE) proposed by Patankar was used to couple the velocity and pressure fields. The first-order upwind scheme was used for the convective terms, and the fully implicit Euler
method was used to advance the time. The successive over-relaxation method was used to iterate each time step.

3. Results and discussion

3.1 Effect of energy supply procedure on MIE

The spark channel radius increases with time for the deposited energy during the spark duration. Test calculations in which the spark channel radius was allowed to increase with time for a methane–air mixture during the spark duration have yielded results that differed by only a few percent or less from those obtained using a fixed spark channel radius. We applied three models in which the spark channel radius changed with time (Fig. 2): the first had a constant spark channel radius during the spark duration (1-section), the spark channel radius in the second model increased halfway through the spark duration (2-section), and the spark channel radius in the third model increased in after four equal periods during the spark duration (4-section).

![Fig.2 Three energy supply procedure models](image)

Because the electrical energy supply is almost constant with time, the spark ignition energy densities are set on the right side of Fig. 2 according to the equation \( Q = q \times t_s \times V \), where \( q \) is the ignition energy density, \( t_s \) is the spark duration, and \( V \) is the volume of the spark channel. The computational results show that the energy supply procedure did not affect the values of the MIE for the methane–air mixture. The agreement between computational results and test calculations demonstrates the validity of our code.

How does the energy supply procedure affect the behavior of the hydrogen-air mixture? Figure 3 shows the temperature history results of hydrogen-air mixture for \( \phi = 1 \), \( L = 0.5 \text{ mm} \) and \( t_s = 20 \mu \text{s} \), with the same ignition energy \( Q_{\text{total, min}} = 0.11 \text{ mJ} \). From the results we can see that with increasing time, the temperature of the 4-section model remained higher and the mixture was successfully ignited. The temperatures of other models gradually decreased, and those mixtures were not ignited. According to our computational results, the MIE for the 4-section model was almost half that for the 1-section model. Thus, the energy supply procedure dramatically affected the MIE values for a hydrogen–air mixture. For this reason, the 4-section model was used for all subsequent hydrogen–air mixture computations.

![Fig.3 Temperature history for three energy supply models](image)

3.2 Effect of spark channel radius on MIE

Sloane\(^{45} \) et al. investigated the effect of the spark channel radius on the MIE for a methane–air mixture by using detailed first-step and third-step reaction models. They reported that even though the values of the MIE were different, the tendencies of the MIE versus spark channel radius were similar. The minimum ignition energies were much more sensitive to a larger spark channel radius, and leveled off at a constant value when the spark channel radius was smaller than a critical value. For a methane–air mixture with detailed chemical reactions, this value was about 0.3 mm. We used our code to determine this value for a hydrogen–air mixture, as shown in Fig. 4, which illustrates the relationship between the MIE and spark channel radius. When the spark channel radius \( R_c \) decreased to 0.15 mm, the MIE leveled off at a value of 0.04 mJ.

![Fig.4 Relationship between MIE and spark channel radius](image)

4. Conclusions

(1) The energy supply procedure dramatically affected the values of the MIE for the hydrogen-air mixture.

(2) When the spark channel radius \( R_c \) decreased to about 0.15 mm, the MIE leveled off at a value near 0.04 mJ.

References

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