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Hi-Speed Imaging and Numerical Analysis of Spark Discharge for Combustion Prediction in Spark-Ignition Engines

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In recent years, the intensification of abnormal weather has increased the importance of climate change measures, and higher thermal efficiency is required for spark-ignition (SI) engines to reduce carbon dioxide emissions. Although mixture lean-burn and high EGR (Exhaust Gas Recirculation) operation are effective, reduced combustion speed makes ignition by spark discharge difficult under excessively lean or highly turbulent conditions, making ignition stability an important issue.

Our research group has also performed ignition stability predictions under high EGR and lean conditions using a combustion prediction model that focuses on the process from spark discharge to flame kernel formation. However, validation of spark discharge behavior in this model has been limited to a narrow range of operating conditions, and existing studies have likewise not sufficiently examined the effects of ambient pressure and flow conditions on discharge behavior. Since the flame kernel formation process strongly depends on energy deposition by spark discharge, inadequate reproduction of the discharge process affects subsequent combustion prediction. Therefore, prior to verifying the flame kernel formation process, validation focusing on the spark discharge process is required.

In this study, spark discharge behavior was recorded by high-speed imaging in a fan-equipped constant-volume chamber, and the effects of ambient pressure and flow velocity on spark discharge behavior were investigated through detailed analysis under various operating conditions. Furthermore, a method for determining model constants based on experimental results was examined, and the applicability of the numerical model for the discharge process was verified through comparison with numerical simulations.

3D numerical simulations were performed using CONVERGE, and the spark discharge model was implemented as a UDF (User-Defined Function) based on existing models. Experiments showed that the discharge tip velocity increased with ambient pressure and gas flow velocity, while its pressure dependence became small at high pressure and the followability saturated at 0.7-0.8. The voltage drop between electrodes was overestimated by the existing formula, and the coefficients related to the gas-phase voltage drop were modified without considering cathode and anode voltage drops.

A comparison of discharge channel length between experiments and predictions was conducted for various ambient pressures and gas flow velocities. The results are shown in Fig. 1. Although the discharge duration became slightly longer at p_a = 1000 kPa and u_{gas} = 18 m/s, the time variation and overall trends were generally reproduced under other conditions. Applying the model reflecting the characteristics of discharge tip motion and the corrected voltage-drop formulation confirmed that the trends in discharge channel extension speed and discharge duration with changes in ambient pressure and gas flow velocity were also generally reproduced in the numerical analysis.

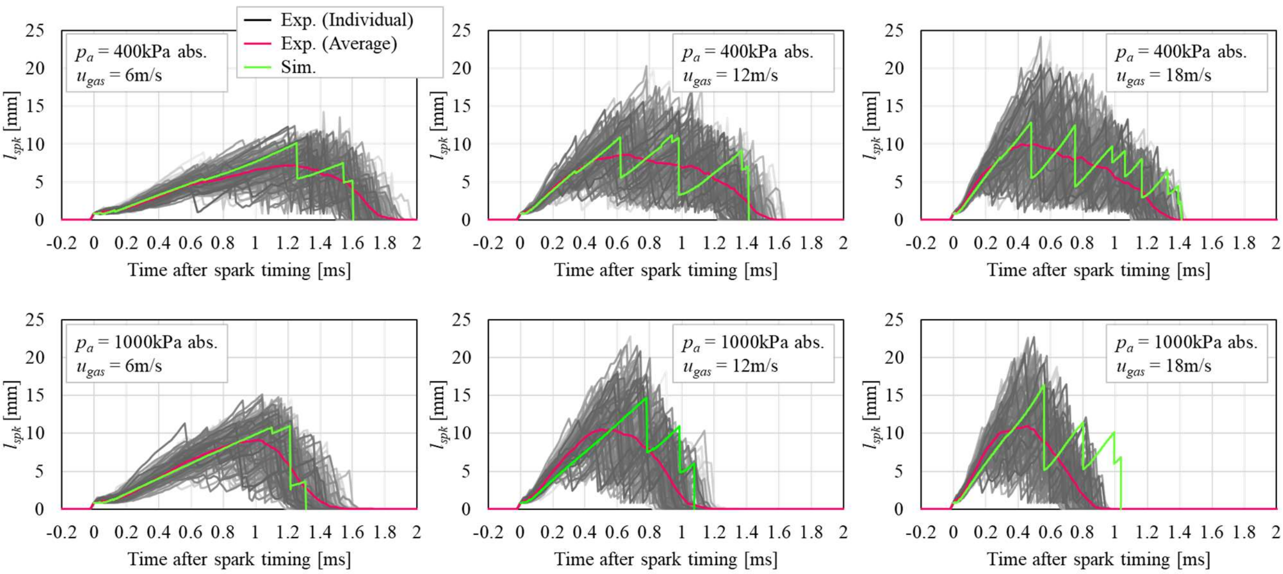

Fig.1 Comparison of experimental and predicted results for discharge channel length