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Research on Abnormal Combustion in Hydrogen-Fueled Spark Ignition Engines

- (Second Report) Construction of Pre-Ignition Model Caused by Hot Surface -

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Pre-ignition in hydrogen engines can be initiated by hot-surface ignition at localized high-temperature components such as spark plugs. In this study, a pre-ignition prediction model applicable to 1D-CFD simulations was developed, focusing on hot-surface ignition. The model concept is illustrated in Fig. 1. Pre-ignition is judged based on the relationship between the contact time of the in-cylinder mixture with a hot surface and the ignition delay time, using the Livengood–Wu integral:

$$LW = \int_{t}^{t+TimeScale(t)} \frac{1}{\tau(t)} dt \geq 1.0$$

where τ is the ignition delay time and $TimeScale$ represents the contact time between the mixture and the spark plug hot surface. The contact time is defined as:

$$Timescale(t) = \frac{L_{plug}}{v_{flow}(t)}$$

The representative flow velocity is evaluated based on the in-cylinder flow field as:

$$v_{flow}(t) = v_{piston} \times (|TR(t)| + |SR(t)|)$$

where v_{piston} is the mean piston speed, and TR and SR are the tumble and swirl ratios obtained from the 1D-CFD simulation.

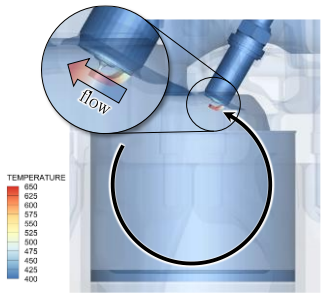

Fig.1 Schematic of the Pre-Ignition Prediction Model Based on Hot-Surface Ignition

The ignition delay time τ is provided by a Neural Network model trained on a database generated using detailed chemical kinetic calculations with Cantera, accounting for equivalence ratio, initial temperature and pressure, EGR fraction, and NO concentration in the residual gas.

Model calibration was conducted using operating conditions under which pre-ignition was induced by spark advance. As shown in Fig. 2, increasing spark plug temperature significantly shortens the ignition delay time, and pre-ignition is predicted when τ becomes shorter than the $TimeScale$. By calibrating the representative spark plug length to L_{plug} = 8 mm, the model successfully reproduced experimental pre-ignition and non-pre-ignition conditions. A sensitivity analysis revealed that the ignition delay shortening effect of NO strongly depends on pressure (Fig. 3), being small at low pressures and pronounced at higher pressures. This pressure dependence explains why pre-ignition does not necessarily occur even at high spark plug temperatures.

In conclusion, the proposed model integrates spark plug temperature, contact time based on in-cylinder flow, and pressure- and NO-dependent ignition delay characteristics, enabling a concise and physically interpretable prediction of pre-ignition occurrence in hydrogen engines.

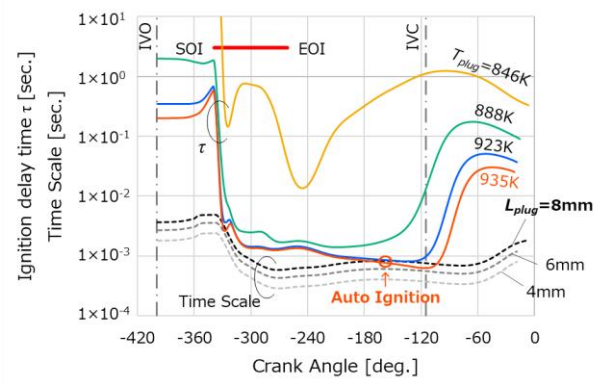

Fig.2 Effect of Spark Plug Temperature on Ignition Delay Time and Time Scale for Model Calibration

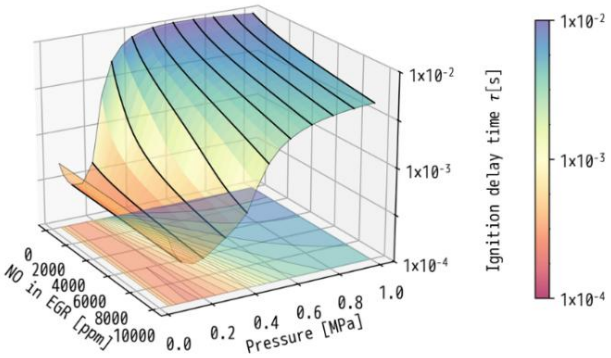

Fig.3 Sensitivity of Ignition Delay Time to NO Concentration and Pressure