

Research on the Effect of Hydrogen Mixing on Knocking in Spark Ignition Natural Gas Engines

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Compressed natural gas (CNG) is an attractive low-carbon fuel, but its slow laminar burning velocity lengthens the combustion duration and lowers thermal efficiency. Blending green hydrogen with CNG (HCNG) shortens the combustion duration. However, the increased reactivity of the end gas may promote autoignition and thus knocking. This study clarifies how hydrogen mixing affects knocking in a spark-ignition (SI) engine.

Experiments were conducted on a single-cylinder SI engine fueled with methane/hydrogen mixtures at hydrogen fractions of 0, 10, 18, and 30 vol%, at an engine speed of 2400 rpm, an IMEP of 1200 kPa, and an excess air ratio of 1.0. The spark timing was swept so that the combustion phasing (MBF50%) ranged from 0 to 25 deg. ATDC. Knocking intensity (KI) was defined as the maximum amplitude of the high-frequency pressure component extracted with a 2500 Hz high-pass filter, and the knocking onset timing as the crank angle at which this amplitude first exceeded ten times the standard deviation of the amplitude evaluated before combustion. Zero-dimensional constant-volume calculations were performed using the GRI-Mech 3.0 mechanism. The initial pressure of approximately 8 MPa and the initial temperature of approximately 1000 K were taken from the measured in-cylinder pressure at knocking onset and the adiabatically compressed end-gas temperature. Sensitivity coefficients of temperature with respect to the rate constants of the elementary reactions were evaluated at the timing of the maximum temperature rise rate.

KI increased monotonically with hydrogen fraction, whereas the onset timing remained almost unchanged. Under the high-pressure end-gas conditions, the chain branching reaction



did not appear among the dominant reactions for any fuel, because on the high-pressure side of the second explosion limit the third-body path



becomes dominant. Instead, reactions involving HO_2 and H_2O_2 showed the highest sensitivity coefficients. The HO_2 formed via (R2) accumulates as H_2O_2 through its self-reaction



and the subsequent thermal decomposition



releases OH radicals. This sequence acts as degenerate chain branching. For pure methane, the oxidation reactions of CH_3 and CH_2O , which supply HO_2 , were dominant, whereas for the hydrogen-blended fuels the formation and decomposition of H_2O_2 became dominant. Hydrogen mixing therefore shifts the rate-limiting step from the supply of HO_2 to the decomposition of H_2O_2 .

Figure 1 shows the H_2O_2 mole fraction histories plotted against the gas temperature. H_2O_2 accumulates in the low-to-intermediate temperature range and decomposes at approximately 1200 K irrespective of the hydrogen fraction. This is because the onset of decomposition is determined solely by the rate constant of (R4)

and the temperature. The amount accumulated just before decomposition, in contrast, increases with the hydrogen fraction, reflecting the amplification of (R3) by the increased HO_2 supply.

Consequently, knocking onset was triggered when the end-gas temperature reached the fuel-independent decomposition temperature of H_2O_2 . Because the comparison was made at matched combustion phasing, the pressure histories, and hence the end-gas temperature histories were nearly common among the fuels. The onset timing therefore remained unchanged. The larger H_2O_2 accumulation at the threshold temperature increases OH production and the heat release rate immediately after ignition, which explains the increased knocking intensity.

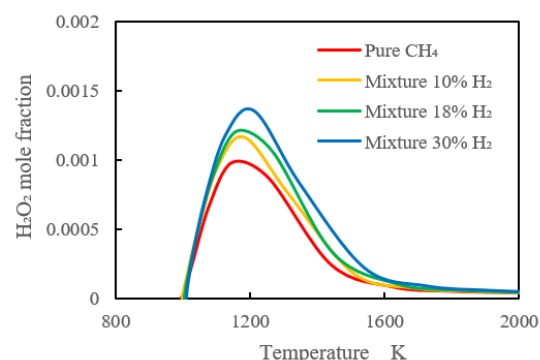


Fig. 1 H_2O_2 mole fraction histories against temperature