

Study of an On-board Fuel Reformer and Hydrogen-Added EGR Combustion in a Gasoline Engine

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ABSTRACT

To improve the fuel economy via high EGR, combustion stability is enhanced through the addition of hydrogen, with its high flame-speed in air-fuel mixture. So, in order to realize on-board hydrogen production we developed a fuel reformer which produces hydrogen rich gas. One of the main issues of the reformer engine is the effects of reformat gas components on combustion performance. To clarify the effect of reformat gas contents on combustion stability, chemical kinetic simulations and single-cylinder engine test, in which hydrogen, CO, methane and simulated gas were added to intake air, were executed. And it is confirmed that hydrogen additive rate is dominant on high EGR combustion. The other issue to realize the fuel reformer was the catalyst deterioration. Catalyst reforming and exposure test were carried out to understand the influence of actual exhaust gas on the catalyst performance. Fresh catalyst showed good performance in generating hydrogen, but an aged catalyst generated only half as compared to a fresh catalyst. So we considered measures to improve catalyst performance. According to EGR reforming performance test with single-cylinder engine using conventional catalyst and an improved catalyst, the improved catalyst showed good performance. Finally, in order to confirm the performance of hydrogen generation and the effects of real reformat gas on EGR combustion, a single-cylinder engine with the fuel reformer was developed. It is confirmed that hydrogen is generated from gasoline and EGR gas by the fuel reformer, and combustion stability under high EGR rate is enhanced by reformat hydrogen.

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INTRODUCTION

Various efforts are under way to improve the fuel economy of internal combustion engines so as to reduce exhaust emissions of carbon dioxide (CO₂), which is regarded as a key priority for contributing to the development of a sustainable mobility society. One approach proposed for improving fuel economy is to adopt a combustion system with a high rate of exhaust gas recirculation (EGR). One key factor to achieve a high EGR combustion system is to ensure the stability of diluted combustion mixture.

The principal measures taken to date to accomplish high EGR combustion in gasoline engines have focused on strengthening ignition or the in-cylinder gas flow[1]. The addition of hydrogen with a rapid flame speed to the mixture has attracted attention as a method for achieving a higher EGR level in combination with these measures. There are reports of research studies concerning reformulated fuel engines for facilitating the on-board supply of hydrogen. Nagano et al.[2] reported the recovery of exhaust gas energy for use in steam reforming of ethanol-containing gasoline by EGR and that the hydrogen-containing EGR gas obtained by the reforming process had the effect of improving thermal efficiency. Alger et al.[3] reported an engine system in which one cylinder of a four-cylinder engine was operated on a mixture richer than

stoichiometric to produce a hydrogen-containing gas, which was then supplied to the remaining three cylinders to improve thermal efficiency.

We propose an on-board fuel reforming system with a simple configuration, which was created by simply adding a catalyst and a reformer injector to the EGR supply line for making comparisons with the results of previously reported studies. It was used in conducting proof-of-concept tests with ordinary gasoline.

CONFIRMATION OF FUEL REFORMING CONCEPT

Reforming Method and Reformat Components

Figure 1 shows the configuration of the on-board reformer/gasoline engine system examined in this study. A reformer is installed in the external EGR line that recirculates a portion of the engine exhaust gas. A steam reforming catalyst is provided inside the reformer into which the fuel to be reformed is injected by a reformer injector. Hydrogen obtained in the reformer is circulated together with the EGR gas through the intake air line to the cylinder for use in combustion. Figure 2 is a conceptual diagram of the fuel reforming process. Gasoline injected into the EGR line by the reformer injector

is mixed with the EGR gas and converted to hydrogen-containing reformat by the steam reforming catalyst in the presence of the high-temperature EGR gas. Figure 3 shows the reformat components found by chemical equilibrium calculations at various reforming catalyst inlet temperatures. The calculations were performed under a steam to carbon molecular number ratio (S/C) of 4, where C was the carbon content of the fuel alone and did not include the C of CO_2 . The reactants used in the calculations were iso-octane that simulated gasoline and exhaust gas components resulting from combustion at a stoichiometric mixture ratio.

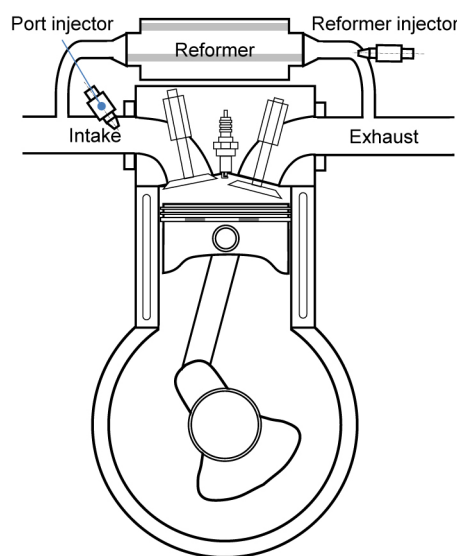


Figure 1. On-board reformer/engine

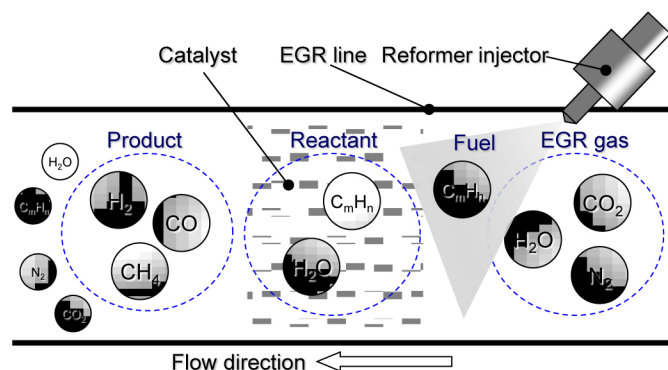


Figure 2. Conceptual diagram of reforming process

The results show that the generated concentrations of hydrogen and carbon monoxide (CO) increase with increasing temperature and that a hydrogen concentration of approximately 6% is obtained at temperatures above 873 K. In contrast, it is seen that the generated concentration of methane is high at lower temperatures. The EGR gas temperature in an actual engine ranges between 673 K and 873 K depending on the engine operating conditions, composition and materials of the exhaust system components and other factors. It is therefore assumed that the temperature condition will be sufficiently high for the actual application of EGR gas. The calculated results thus revealed the potential for obtaining a hydrogen concentration as high as approximately 6% by reforming the fuel in the presence of EGR gas in an actual engine. On the other hand, because the

generated concentrations of methane and CO are also high, it was necessary to confirm their effect on combustion performance, as will be described in the following section.

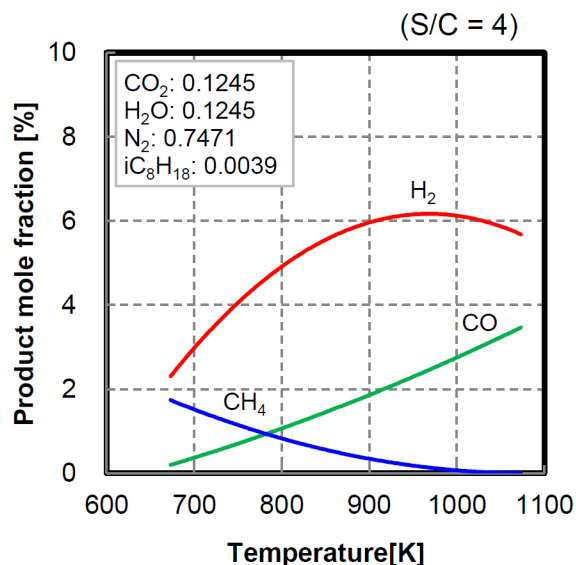


Figure 3. Equilibrium calculation results for reformat

Effect of Reformat Components on Flame Speed

In this fuel reforming system, hydrogen with a rapid flame speed is added as a means of obtaining a high EGR condition by suppressing the moderation of the combustion period that occurs as the EGR rate is increased. Therefore, the flame speed of the air-fuel mixture is presumed to be a key factor affecting performance.

The results of the equilibrium calculations for the reformat in Figure 3 indicated that it also contained methane and CO, in addition to hydrogen. In order to determine the effect on combustion of adding these components to the air-fuel mixture, the flame speed of the mixture was calculated for different additive rates of the reformat components using the CHEMKIN-PRO chemical kinetic simulation software.

The calculation conditions used are shown in Table 1. A five-component gasoline model (231 chemical species, 1,354 reactions, –2008) developed by the Model Fuels Consortium was used as the reaction model [4]. The laminar flame speed was calculated with a 1-dimensional freely propagating premixed laminar flame model. The in-cylinder conditions were simulated by inputting an engine speed of 1200 rpm, indicated mean effective pressure (IMEP) of 700 kPa and ignition timing of 30 deg. before top dead center (BTDC). The initial temperature and pressure were set at 700 K and 1000 kPa, respectively. The reactants consisted of iso-octane as the principal fuel and the reformat. The total heat value was kept the same under all the conditions by reducing the quantity of iso-octane corresponding to the heat value equal to the additive rate of the reformat components. The quantity of air inducted was adjusted so as to obtain a stoichiometric mixture ratio under all of the conditions used.

Table 1. Calculation conditions

Calculation Scheme	CHEMKIN-PRO 1-dimensional freely propagating premixed laminar flame model
Reaction Species/Number	231/1354
Initial Temperature	700 K
Initial Pressure	1000 kPa

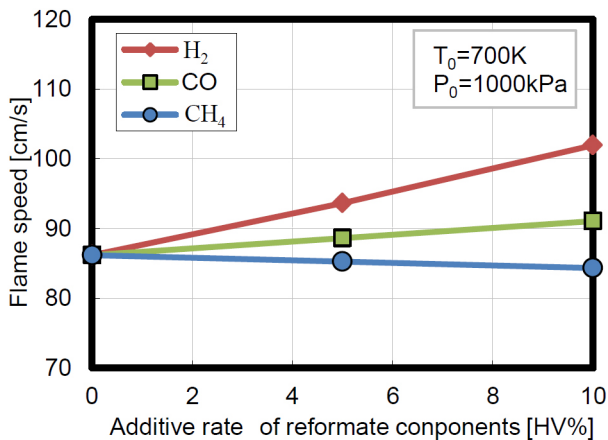
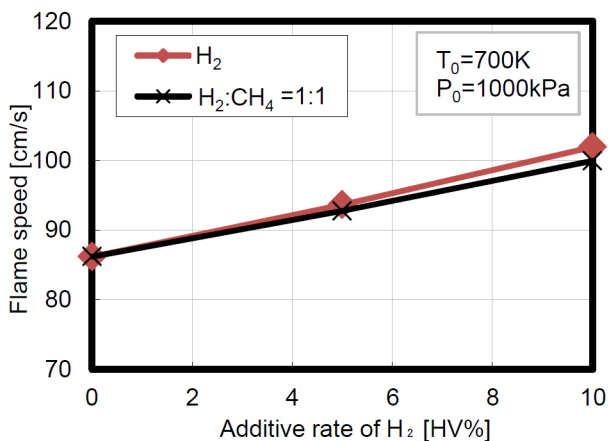


Figure 4. Flame speed of reformate gas components added to iC8H18 mixture

Figure 5. Flame speed of H₂ and component mixture (H₂ + CH₄) added to iC₈H₁₈ mixture

The calculated flame speed results are shown in Figure 4. The heat value fraction (HV %) on the horizontal axis indicates the share of the heat generated by the added reformate component as a percentage of the total heat value of the fuel injected into the cylinder. The results indicate that the flame speed increases when hydrogen and CO are added and that hydrogen produces the largest rate of increase in the flame speed. Hydrogen increases the flame speed by approximately 18.3% at an additive rate equal to an HV fraction of 10%. On the other hand, when methane is added, the flame speed decreases with an increasing additive rate. The rate of reduction is around 1.2% at an additive rate equal to an HV fraction of 10%. That is attributed to methane's slower flame speed compared with that of iso-octane [5]. Presumably, the addition of methane would have the effect of moderating combustion.

Figure 5 shows the calculated laminar flame speeds for the addition of equal proportions of hydrogen and methane and for the addition of hydrogen alone. When the results are normalized to the additive rate of hydrogen alone, the flame speed of the hydrogen/methane-containing mixture is approximately 2% slower than that seen for hydrogen alone at an additive rate equal to an HV fraction of 10%.

The results in Figure 4 for methane alone showed a rate of reduction in the flame speed of approximately 1.2% when the additive rate of methane was increased from an HV fraction of 0% to 10%. Based on that result, the reduction rate of approximately 2% can be estimated to be the effect of the additive mixture obtained by adding together the effects of the individual reformate components.

On the other hand, the rate of reduction in the flame speed attributed to methane is very small at approximately 1/15 of the 18.3% rate of increase in the flame speed when the additive rate of hydrogen is increased from an HV fraction of 0% to 10%. This implies that the effect of methane is not large enough to cancel the effect of hydrogen on improving combustion. Accordingly, the additive rate of hydrogen governs the effect of the reformate on the flame speed. This suggests that hydrogen's share of the total heat value of the air-fuel mixture is a key parameter for evaluating various performance attributes of a reformulated fuel engine.

EFFECT OF INDIVIDUAL REFORMATE ADDITIVES ON ENGINE PERFORMANCE

Addition of Individual Reformate Additives

In order to ascertain the effect of the reformate on combustion performance, experiments were conducted in which the principal reformate components of hydrogen, CO and methane were added individually to the air-fuel mixture used in the single-cylinder gasoline engine. Table 2 lists the engine specifications, and Figure 6 is a schematic diagram of the experimental apparatus used. The reformate components were supplied individually from a gas cylinder under pressure regulated by a gas regulator and injected into the intake port by a gas injector. The injection quantity was measured by a mass flow meter and adjusted according to the injection duration of the gas injector. The in-cylinder pressure was measured with a pressure sensor installed inside the cylinder and IMEP was calculated from the measured result.

Table 2. Engine specifications

Engine type	Single cylinder
Bore × Stroke	93 mm × 81.4 mm (553 cc)
Compression Ratio	12:1
Fuel	Japanese High-Octane Gasoline (100 RON, S < 10 ppm)