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Influence of hydrogen addition on the operating range, emissions and efficiency in lean burn natural gas engines at high specific loads

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ABSTRACT

Power to Gas has attracted much attention as a solution to handle the electricity overproduced from renewable energy. This overproduced electricity can be converted into H_2 and injected into the existing natural gas grid. Therefore, efficient and safe usage of H_2 enriched natural (HNG) gas is a key issue to spread Power to Gas further. In this paper, the influences of H_2 addition on the engine combustion process is discussed, focusing on large-bore lean burn gas engines operated at high specific loads. The experimental setup consists of a single cylinder research gas engine with a displacement of 4.77 L. The results show a big influence of the addition of H_2 on the operating range and emissions even with small amounts of H_2. The misfire limit extends to the leaner side, while knocking must be prevented by a later ignition timing (IGT). Pre-ignition phenomena are limiting the operating range at richer conditions with rising H_2 amounts. While NO_x emissions increase, unburned hydrocarbon (THC) and formaldehyde (HCHO) emissions decrease due to an enhanced combustion. This and the leaner operating conditions, which can overcompensate the actual NO_x increase, facilitate a higher efficiency, which is discussed based on a detailed loss analysis.

1. Introduction

The domestic share of renewable energy has been growing rapidly with an increased interest in global warming. Although usage of renewable energy offers some inherent advantages, the output from renewable energy can fluctuate strongly due to external conditions and the electricity can be overproduced at times of low demand. Hence, effective utilization of the surplus electricity has become an important concern for a further increase in renewable energy. Power to Gas is one of the promising solutions for this issue [1]. The surplus electricity could be used for H_2 production, which can be injected into the existing natural gas grid. This has the advantage that the produced H_2 can be stored and transported by the pipe line with minimum infrastructure cost. The injected H_2 is mixed with natural gas in the grid and used as H_2 enriched natural gas in gas-fired appliances and facilities. Therefore, the influence of H_2 addition on the combustion process has to be investigated for a widespread of Power to Gas applications [2]. Another opportunity of Power to Gas is the methanation of H_2. This would have the disadvantage of losses during the conversion process, so direct injection of H_2 in the gas grid is intended, if the technical restrictions for gas-fired applications are harmless enough and the operation is not limited. Table 1 summarizes the combustion properties of H_2 and CH_4, which is the major component of natural gas. The high reactivity as well as diffusivity of H_2 lead to a higher laminar burning velocity, lower required minimum ignition energy and wider flammability compared to CH_4. These characteristics have drawn much attention to H_2 as an additive to improve the deteriorated combustion quality in lean burn operation fueled with unblended natural gas. Therefore, the combustion properties of H_2 enriched natural gas have been closely investigated in the past decades. The remarkable findings are summarized in the following.

- The laminar burning velocities of the blended CH_4—H_2 fuels are always smaller than those obtained by averaging the values of the laminar burning velocity of the pure fuels according to their molar proportions. In addition, lower H_2 fractions less than 50 vol-% have a slight impact on an increase of the laminar burning velocity [3].

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Table 1
Combustion properties of CH_4 and H_2 For detailed boundary conditions see [38].

	Unit	CH_4	H_2
Laminar burning velocity	cm/s	48	290
Minimum ignition energy	10^{-5} J	28	2
Quenching distance	mm	2.03	0.64
Flammability	$\lambda_{min}-\lambda_{max}$	0.6–2	0.14–10
Stochiom. air ratio	kg/kg	17.1	34.2
Lower heating value	MJ/kg	50	120
Methane number	–	100	0

- Turbulent burning velocities are significantly raised by a small amount of H_2 added to CH_4. This effect is pronounced particularly in lean air/fuel mixtures, while it becomes less effective towards stoichiometric air/fuel ratios (λ) [4].
- The auto-ignition characteristics are modestly affected by the lower H_2 fractions in the fuel (<20 vol-%). On the other hand, volumes fractions of 50% H_2 in the fuel result in a substantial reduction in ignition delay times [5].
- Quenching distances are considerably reduced by a small blending ratio of H_2 addition at lean air/fuel ratios [6].

Apart from the ignition delay, the data in the past studies were obtained at atmospheric pressure and temperature due to the difficulties in the measurement.

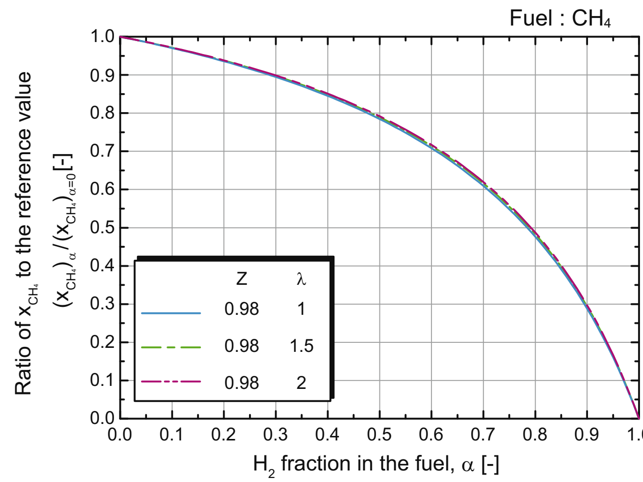
In addition, the engine combustion process of H_2 enriched natural gas has been investigated in previous studies. Although there are differences in the operating conditions as well as engine specifications among those studies, similar trends in the combustion behavior and emission characteristics have been observed in most cases. Due to the lower required minimum ignition energy and higher burning velocity of H_2 enriched natural gas, H_2 addition reduces both the first flame development and the flame propagation periods [7–17]. The decrease in the burning duration retards the maximum brake torque timing (MBT), which requires optimization of the spark ignition timing according to the H_2 amount in the fuel. H_2 addition stabilizes the combustion process in lean burn operation and contributes to an extension of the lean operating limit [7,10–12,14,15,18,19]. Regarding the emission characteristics, the evaluation at a given lambda shows that THC emissions are decreased with the H_2 addition [7,9,10,12,13,15,19–26]. There are two reasons leading to a decrease in THC emissions. One is attributed to the higher H/C ratio of H_2 enriched natural gas, while the other is attributed to the improvement in the combustion process, which is caused by the smaller quenching distance and higher burning velocity of H_2 enriched natural gas. The former contribution can be theoretically estimated from the chemical equation of CH_4 containing H_2, which is expressed by the following equation:

$$\begin{aligned}&(1-\alpha)CH_4+\alpha H_2+\lambda\{(2-1.5\alpha)O_2+3.773(2-1.5\alpha)N_2\}\\&\quad\rightarrow Z\{(1-\alpha)CO_2+(2-\alpha)H_2O+(\lambda-1)(2-1.5\alpha)O_2\}+(1-Z)\\&\qquad\times\{(1-\alpha)CH_4+\alpha H_2+\lambda(2-1.5\alpha)O_2\}+3.773\lambda(2-1.5\alpha)N_2,\end{aligned}$$

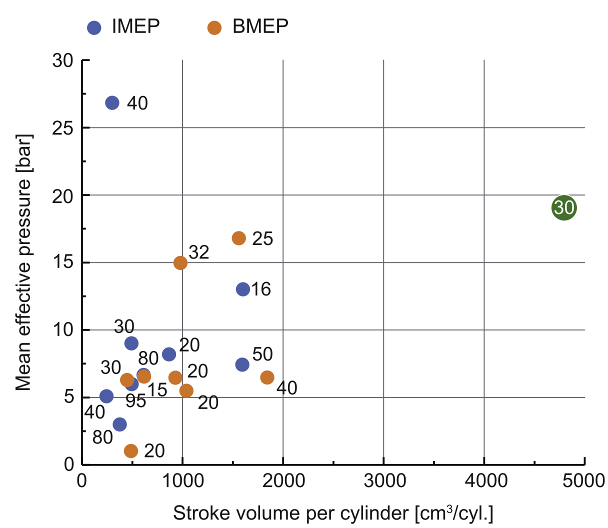
where α is the H_2 fraction in the fuel and Z is the combustion efficiency. In this equation, the unburned products are assumed to be of the same compositions as the reactants. Based on this equation, the mole fraction of the unreacted hydrocarbon in the combustion products, x_{CH_4} can be calculated as follows.

$$x_{CH_4}=\frac{(1-Z)(1-\alpha)}{1-0.5\alpha Z+4.773\lambda(2-1.5\alpha)}$$

The ratio of x_{CH_4} to the reference value at $\alpha=0$ is shown in Fig. 1a. The reduction rate of the unreacted CH_4 emissions decreases exponentially with an increase of the H_2 addition. The result also suggests that the reduction rates are always smaller than



(a) Influence of H_2 amount on THC emission due to lower hydrocarbon in the fuel



(b) Results of literature review with focus on load and displacement volume. Values are H_2 amount in mol.%. Green circle represents this study

Fig. 1. Influence of hydrogen on THC emissions due to lower hydrocarbon in the fuel/Values of MEP and displacement of past studies.

volume fractions of H_2 in the fuel. More specifically, 30 mol-% H_2 addition leads to nearly 10% reduction of unreacted CH_4 emissions. This result indicates that an improvement in the combustion process becomes the major effect of the THC decrease, if a small amount of H_2 realizes drastic reduction of THC emissions. In contrast to the THC emissions, the NO_x emissions are increased with a rising H_2 amount in the fuel at a given λ [7,9,14,19–21,23–26]. This is caused by the higher combustion temperatures, which result from the shorter combustion duration as well as the higher adiabatic flame temperature of H_2 enriched natural gas. However, the extended lean operation with HNG can compensate the higher NO_x emissions while keeping the THC emission and the efficiency at a high level.

As mentioned above, a lot of findings have been accumulated in previous studies. In most cases, H_2 addition has a positive effect on the combustion process of lean burn gas engines. On the other hand, most of the studies have targeted small sized automotive engines or truck sized engines and thus there is a lack of information on industrial gas engines with lower speeds and larger bores.