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# Effects of Air-fuel Ratio and Hydrogen Fraction on Combustion Characteristics of Hydrogen Direct-Injection Gasoline Engine

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**Abstract.** Effects of air-fuel ratio and hydrogen fraction on engine combustion at the conditions of locally rich hydrogen and lean-burn mode have been experimentally carried out on a hydrogen direct-injection (HDI) and gasoline port-injection engine. The test results showed that both excess-air ratio and hydrogen affect the HDI combustion. The peak cylinder pressure was decreased by 45% (3.9% hydrogen fraction) and 23% (10.5% hydrogen fraction) when the excess-air ratio was increased from 1 to 1.5. Hydrogen, which compensates the loss of cylinder pressure and heat release rate caused by lean burn, effectively improves the engine performance at lean burn operation. In addition, when the excess air ratio was set at 1.2, the rise in hydrogen fraction from 3.9% to 10.5% caused a 51.2 % increase in peak cylinder pressure and 101% increase in maximum heat release rate. The maximum cylinder temperature and exhaust temperature was increased firstly and then decreased afterwards with an increase in excess-air ratio. The increase in hydrogen fraction resulted in the acceleration of maximum cylinder temperature, but the exhaust temperature is not that much affected.

## 1. Introduction

A large part of the world energy is consumed by motor vehicles, which are operated by using gasoline and diesel fuel derived from crude oil that is a form of energy with limited reserves. Furthermore, one of the most important factors of environmental pollution is motor vehicles. Energy demand and emission regulations are forcing automotive researchers to explore superior fuels and develop new combustion technologies to comply with stringent emissions regulation being adopted worldwide and continue the quest for improving engine performance. To facilitate the enhancement in performance of engines pure hydrogen engine and the addition of hydrogen to conventional gasoline fuel in the sparking ignition (SI) engine have been proposed by many researchers. As hydrogen offers many advantages over the other fuels. Hydrogen gas is characterized by a rapid combustion speed, wide combustible limit, high lower calorific value and low minimum ignition energy. Furthermore, CO and HC emissions could be significantly reduced by using comparably small amounts of hydrogen on an SI engine.

Hydrogen engine has been explored by huge body of researchers. Anuj Pal and Avinash Kumar Agarwal [1] investigated the effects of compression ratio on the combustion, performance and emissions characteristics of a prototype laser ignited hydrogen fueled engine. They found that higher compression ratio improved the engine performance (increased peak cylinder pressure, rate of pressure rise and heat release rate). Brake thermal efficiency improved with increasing compression ratio,



which led to lower fuel consumption for generating desired power output, thereby improving fuel economy. Exhaust gas temperature reduced upon increasing the compression ratio. S. Verhelst [2] reviewed the advancements made in plotting the possibilities offered by direct injection of hydrogen, in-cylinder heat transfer, modeling and combustion strategies (on an engine as well as vehicle level). These efforts have resulted in impressive efficiency numbers, both at peak and part load operation, while keeping emissions far below regulatory limits and reaching satisfactory specific power outputs. However, as hydrogen has the lower volumetric energy density and higher combustion temperature, pure hydrogen fueled engine produces lower power output and much higher  $\text{NO}_x$  emissions than gasoline fueled engine at stoichiometric air-fuel ratio. Furthermore, when pure hydrogen is used, the engines are prone to pre-ignition due to hydrogen's lower ignition energy, wider flammability range and shorter quenching distance. In addition, when pure hydrogen is burned in the engine, the heat release is very fast, and the temperature is high. Thus the engine could potentially emit high levels of  $\text{NO}_x$  and engine reliability is challenged because of high thermal load.

To overcome these problems, a reasonable method to enhance combustion is to use hydrogen as an additive to fossil fuels. In this way, the advantages of the hydrogen gas can be used effectively to improving combustion and emissions performance of conventional fuels, for example, increasing combustion speed, improving the diffusion properties of the mixtures, increasing cylinder pressure and reducing emissions. Seung Hoon oh et al. [3] experimentally investigated the influence of hydrogen nano bubble on the combustion characteristics of a gasoline engine. The engine test results show that the power of a gasoline engine with hydrogen nano bubble gasoline blend was improved to 4.0% (27.00 kW), in comparison with conventional gasoline (25.96 kW), at the engine load of 40%. Karagozet al. investigated the effect of hydrogen and oxygen addition as a mixture on emissions and performance characteristics of a gasoline engine. According to the results, the brake power and brake thermal efficiency were increased by means of hydrogen addition. F. Amrouche et al. Authors in [4] carried an experimental investigation of hydrogen enriched gasoline in a Wankel rotary engine. The experimental results showed that adding hydrogen to gasoline in the engine improved the thermal efficiency and the power output. Wang et al.[5] studied the performance of a hydrogen-blended gasoline engine at lean and the wide open throttle conditions. The test results demonstrated that the hydrogen blending contributed to the raised thermal efficiency and shortened flame development and propagation durations.

## 2. Experimental device and procedure

### 2.1. Experimental device

Table 1 showed the main parameters of 4 cylinders engine used for test. The engine was modified to realize the gasoline port injection and hydrogen in-cylinder direct injection. The self-developed ECU could precisely control ignition timing, fuel injection time and injection pulse width, hydrogen injection time and injection pulse width.

Table 1. Engine specifications

Item	Value
Type of engine	4cylinders,16 valves
Bore×Stroke(mm)	82.5×84.1
Compression ratio	9.6
Displacement(mL)	1798
Rated power(kW)	118(5000~6200 r/min)
Maximum torque (N·m)	250(1500~4200 r/min)

The main instruments used in the experiment include dynamometer, dynamometer control system, combustion analyzer, exhaust analyzer, fuel consumption meter, hydrogen mass flow meter and lambda sensor. Engine speed, engine torque, engine power, intake and exhaust pressure, intake and exhaust temperature, intake flow, cooling water temperature, oil pressure, oil temperature and other real-time data were recorded by the data acquisition module of a CW160 drum type eddy current

dynamometer. Combustion data were sampled and treated mainly by AVL combustion analyzer, whose hardware systems included work stations, data acquisition unit, signal amplifier and corresponding cylinder pressure sensors. AVL cylinder pressure sensor and superscript meter were used to measure real-time data of engine cylinder pressure. Combustion signals were firstly amplified by signal amplifier, and then transferred to combustion analyzer. Therefore, some functions could be achieved such as engine calibration measurement and display computation by DS0928 combustion analysis software, combined with engine parameters and physical and chemical characteristics of the fuel. Real-time cylinder pressure and combustion data could be monitored and computed by combustion analyzer, then combined with engine parameters and, physical and chemical properties of fuel. Heat release rate and cylinder temperature could be achieved by computing.

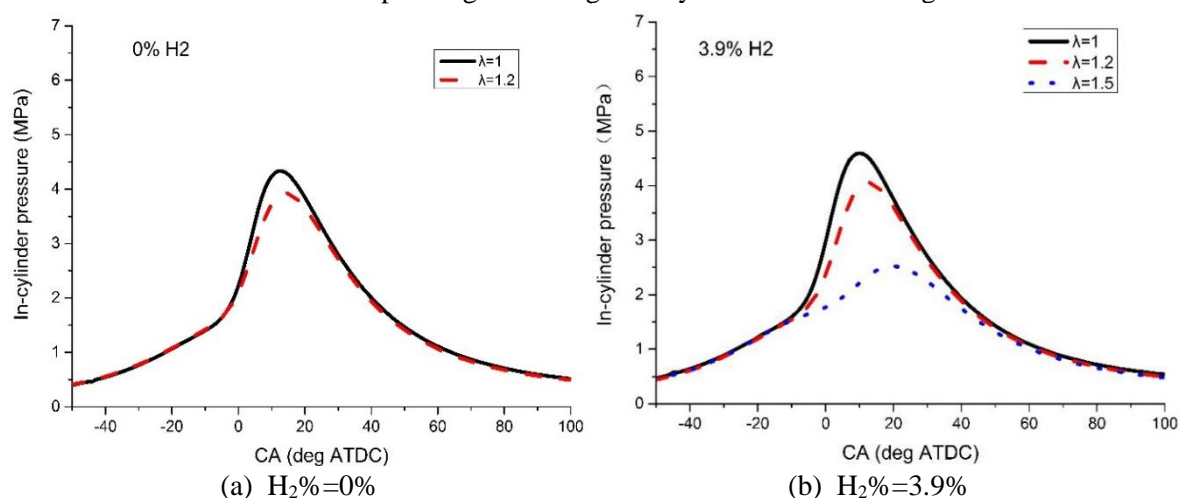
## 2.2. Experimental procedure

The tests were performed at a constant engine speed of 1500 rpm, which could represent the engine speed in the typical city-driving conditions with a heavy traffic. The quantity of hydrogen was changed by adjusting hydrogen injection pressure and hydrogen injection pulse width. The percentage of hydrogen was defined as hydrogen volume accounted for the volume of air input, and the hydrogen fraction included 3.9%, 5.3%, 7.2%, 8.9% and 10.5%. The excess-air ratio was controlled by changing fuel supply quantity under different hydrogen fractions. The tests can determine the best ignition advance angle by changing different ignition timings at different excess-air ratio and different hydrogen fractions. Tests data of engine cylinder pressures was recorded by combustion analyzer.

## 3. Result and discussion

### 3.1. Effects of hydrogen fraction and excess-air ratio on cylinder pressure

Cylinder pressure curves are important basis for engine burning conditions. Fig.1 (a~f) show in-cylinder pressure curves versus the variation of excess-air ratio when the percent of hydrogen is arranged at 0%, 3.9%, 5.3%, 7.2%, 8.9% and 10.5%. Different peak cylinder pressure and their corresponding crank angles when  $\lambda=1$ ,  $\lambda=1.2$  and  $\lambda=1.5$  at different hydrogen fractions are shown in table 2. The peak cylinder pressure decreases and the corresponding crank angle lags with the increase of the excess-air ratio at the same hydrogen fraction (Fig.1). Moreover, the trends are more obvious when  $\lambda=1.5$  than that of  $\lambda=1.2$ . This is mainly because with the increasing of the excess-air ratio, gas mixture of cylinders gets lean, the gross caloric value of fuel reduces. Therefore, the combustion temperature in cylinder decreases and combustion rate slows significantly. Incomplete combustion and burning loss increase gradually, as a result, the cylinder pressure decreases and the corresponding crank angle delays with the increasing of the excess-air ratio.



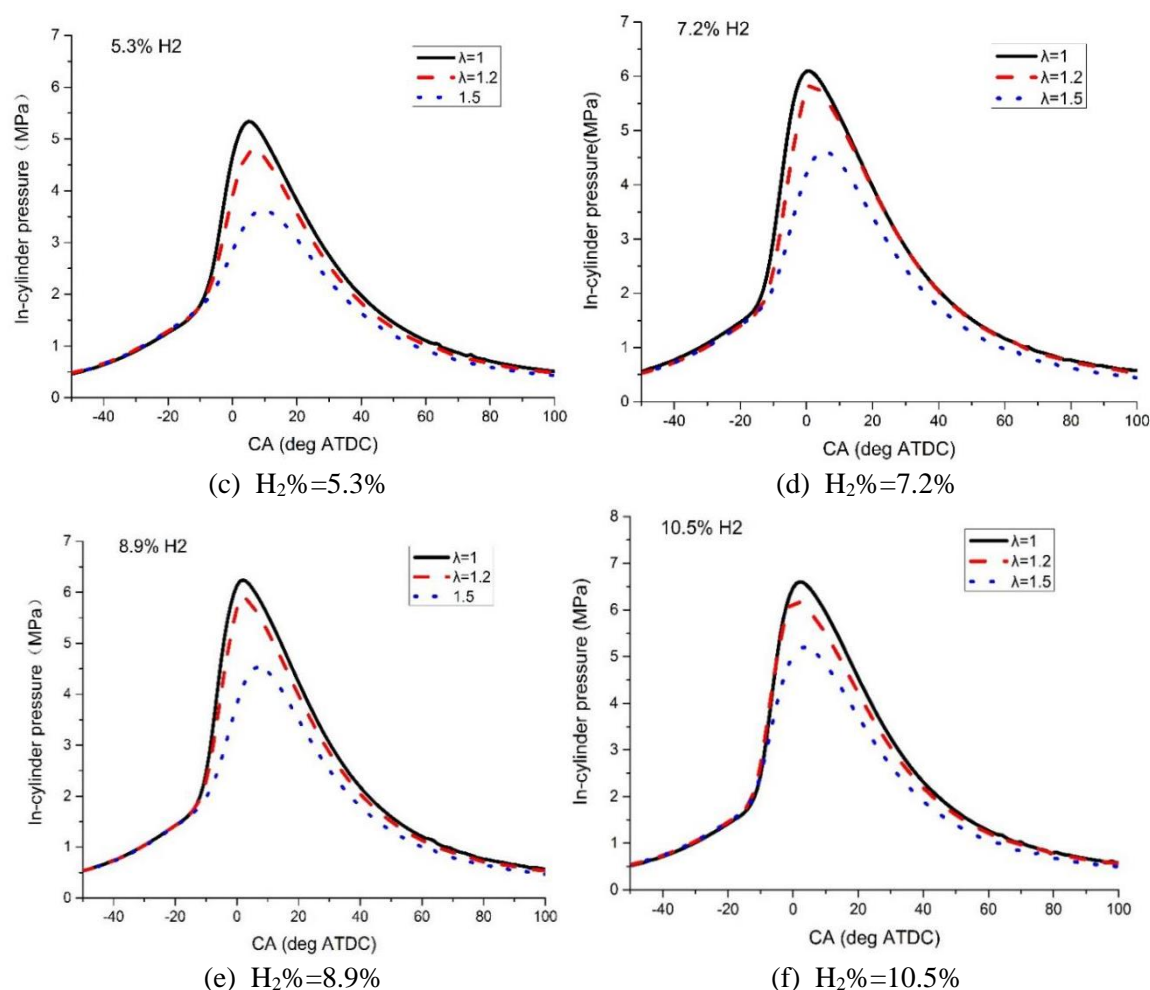


Figure 1. In-cylinder pressure of different hydrogen fractions (0%, 3.9%, 5.3%, 7.2%, 8.9%, 10.5%).

Table 2. Peak cylinder pressure ( $P_{\max}$ ) and corresponding crank angle ( $\theta_{P_{\max}}$ ) of different excess-air ratio and hydrogen fractions

ratio and hydrogen fractions			
Hydrogen fractions	Lambda=1Pmax (MPa)/θPmax (°)	Lambda=1.2Pmax (MPa)/θPmax (°)	Lambda=1.5 Pmax (MPa)/θPmax (°)
0%	4.3/13	3.9/14	Misfire
3.9%	4.6/10	4.1/12	2.5/20
5.3%	5.3/5	4.7/7	3.6/9
7.2%	6.1/1	5.8/2	4.6/5
8.9%	6.2/2	5.9/2	4.5/7
10.5%	6.6/2	6.2/2	5.1/4

It is calculated from table 2, the peak cylinder pressure fall by 10% and 45%, respectively 0.5Mpa and 2.1Mpa at  $\lambda=1.2$  and  $\lambda=1.5$  than that of  $\lambda=1.0$  when the percent of hydrogen is 3.9%. Meanwhile, the corresponding crank angle delays  $2^\circ$  CA and  $8^\circ$  CA. Nevertheless, when the percent of hydrogen increases to 10.5%, the peak cylinder pressure reduces by 6% and 23% and the corresponding crank angle delays  $0^\circ$  CA and  $2^\circ$  CA. Results show that, with the percent of hydrogen increases, the gaps of peak cylinder pressure and the corresponding crank angle under different excess-air ratio reduce. This is because with the increase of the percent of hydrogen, hydrogen addition effectively makes up for the slow speed caused by lean combustion. Furthermore, due to the fact that hydrogen has much higher adiabatic flame speed, much lower ignition energy and much

faster diffusion speed than gasoline at atmospheric condition, small amount of hydrogen added to the intake air can significantly improve the combustion speed in cylinder. Obviously, hydrogen fraction effectively improves power capability of the gasoline engine at lean-burn conditions.

### 3.2. Effects of hydrogen fraction and excess-air ratio on heat release rate

To understand combustion condition in cylinders sufficiently, Fig.2 indicates the trend of heat release rate with the excess-air ratio when the percent of hydrogen is in 3.9% and 10.5%. As shown in figure 2, the maximum heat release rate and the corresponding crank angle decrease with the increasing of the excess-air ratio. In addition, at the same excess-air ratio, the peak heat release rate and the corresponding crank angle are increased with the increasing of the hydrogen fraction. For example, when  $\lambda=1$ , the percent of hydrogen increases from 3.9% to 10.5%, the peak heat release rate increases by 91% and the advance of corresponding crank angle is  $10^\circ$ . Nevertheless, when the excess-air ratio increases to 1.2, with the same variation of hydrogen fraction, the peak heat release rate increases by 101% and the advance of corresponding crank angle is  $13^\circ$ . Furthermore, when the excess-air ratio increases to 1.5, under hydrogen addition of 3.9%, owing to lean fuel and little hydrogen fraction there has been a phenomenon of misfire. By analysis, the results showed that the bigger of the excess-air ratio, the more efficiently hydrogen addition enhancing the heat release rate. This is attributed to that the hydrogen is directly injected into the cylinder in the compression stroke, forming local rich hydrogen and whole layered mixture. Due to low hydrogen ignition energy and high adiabatic flame speed, the ignition delay period shorten. Moreover, flame can quickly get the whole combustion chamber. As a result, the mixture burns more fully, cycle indicated work and the heat release rate increase obviously.

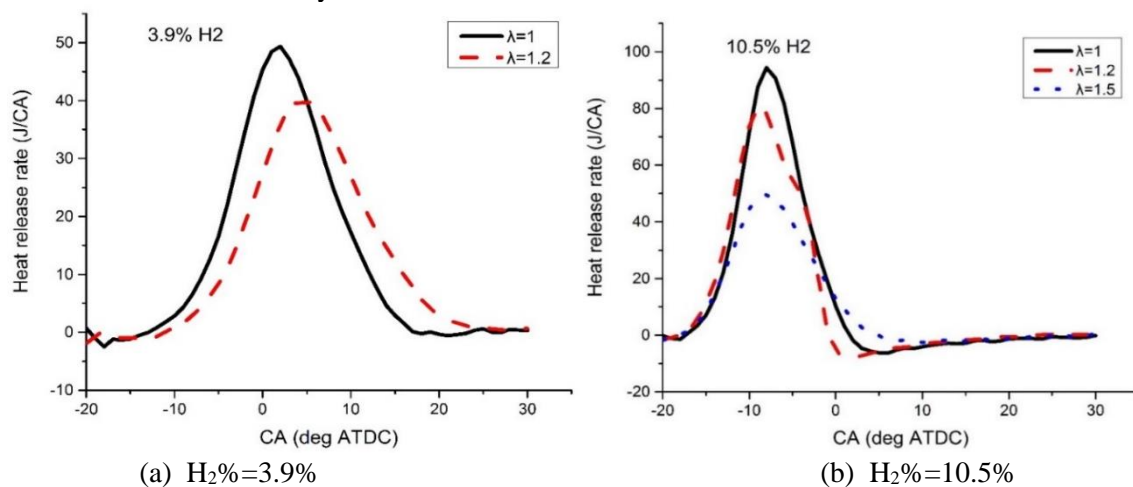


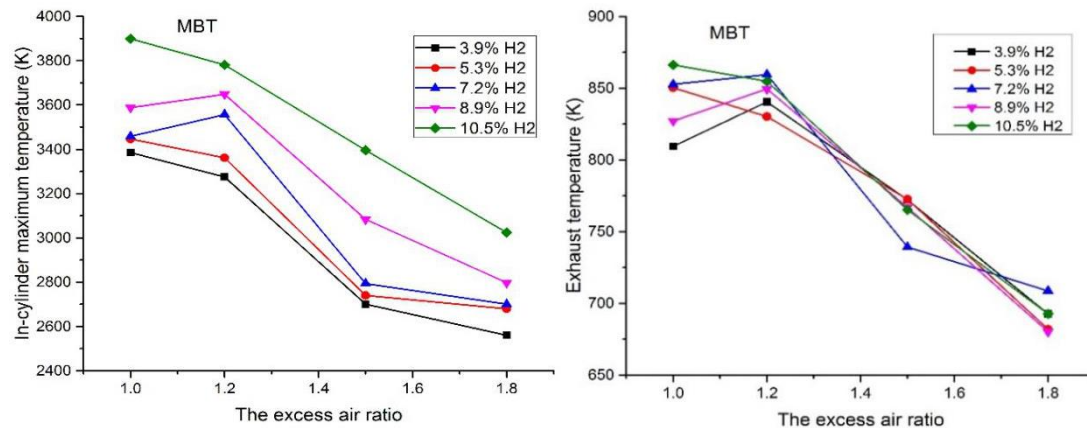
Figure 2. Heat release rate of different hydrogen fractions (3.9%, 10.5%).

### 3.3. Effects of hydrogen fraction and excess-air ratio on heat release rate

The combustion temperature of the second cylinder and the exhaust temperature versus the variation of the excess-air ratio at different hydrogen fractions and the speed of 1500rpm are shown in Fig. 3. In the compression stroke and power stroke, the air-fuel ratio is the main factor influencing the engine combustion process and exhaust temperature. When the excess-air ratio increases from 1 to 1.2, the oxygen ratio in cylinder increases firstly, causing a more complete combustion, then the highest temperature in cylinder and exhaust temperature rise slowly. When  $\lambda$  is greater than 1.2, because the mixture gets leaner gradually, combustion heat cut down, meanwhile, the highest temperature in cylinder and exhaust temperature drop rapidly. Furthermore, when  $\lambda$  is greater than 1.2, the maximum combustion temperature with bigger hydrogen fraction is obviously higher than that of smaller hydrogen fraction. However, the differences of the exhaust temperature with different hydrogen fractions are little. This is because hydrogen addition effectively compensates for the problems such as deterioration of combustion caused by lean combustion. Moreover, hydrogen



addition speeds up the flame propagation speed, shortens the flame development period and promotes the fuel to good use. To conclude, hydrogen addition is beneficial to improve thermal power conversion efficiency and reduce exhaust temperature.



(a) In-cylinder maximum temperature (b) Exhaust temperature  
Figure 3. In-cylinder maximum temperature and exhaust temperature versus the excess-air ratio.

#### 4. Conclusions

(1) For a fixed hydrogen fraction, the increase in air-fuel ratio results in a similar variation of peak cylinder pressure and heat release rate, which both decrease. Meanwhile, the occurrence timing of peak cylinder pressure is retarded.

(2) Hydrogen fraction effectively increases the peak cylinder pressure and heat release rate. At  $\lambda = 1.2$ , peak cylinder pressure is increased by 51.2% and heat release rate is increased by 101% when hydrogen fraction is 10.5% than that of 3.9%. While  $\lambda = 1.5$ , when hydrogen fraction increases from 3.9% to 10.5%, the peak cylinder pressure dramatically increases by 104%. Furthermore, it broadens the scope of air-fuel ratio and extends lean limits.

(3) The maximum cylinder temperature and exhaust gas temperature firstly increase and decline afterwards, and achieves peak at  $\lambda = 1.2$ . The maximum cylinder temperature was significantly increased with the increase of hydrogen fraction.

#### References

- [1] Sunil Malla. Assessment of mobility and its impact on energy use and air pollution in Nepal, *Energy*, 2014, 69:485-496.
- [2] Jia-Shiun Chen. Energy efficiency comparison between hydraulic hybrid and hybrid electric vehicles, *Energy*, 2015, 8:4697-4723.
- [3] Adem Ugurlu, Semiha Oztuna. A comparative analysis study of alternative energy sources for automobiles. *Int J Hydrogen Energ*, 2015, 40, 11178-11188.
- [4] Wonsik Choi, Shishan Hu, Meilu He, et al. Neighborhood-scale air quality impacts of emissions from motor vehicles and aircraft. *Atmos Environ*, 2013, 80:310-321.
- [5] Madhujit Deb, G.R.K. Sastry, P.K. Bose, Rahul Banerjee. An experimental study on combustion, performance and emissions analysis of a single cylinder, 4-stroke DI-diesel engine using hydrogen in dual fuel mode of operation. *Int J Hydrogen Energ*, 2015, 40:8586-8598.