

High-Efficiency and Low-NO_x Hydrogen Combustion by High Pressure Direct Injection

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ABSTRACT

Hydrogen can be produced from various renewable energy sources, therefore it is predicted that hydrogen could play a greater role in meeting society's energy needs in the mid- to long-term. Conventional hydrogen engines have some disadvantages: higher cooling loss results in low thermal efficiency and abnormal combustion (backfire, pre-ignition, higher burning velocity) limits high load operation. Direct injection is an effective solution to overcome these disadvantages, but combustion methods that enable both high efficiency and low NO_x have yet to be studied in enough detail.

In this research, high-efficiency and low-NO_x hydrogen combustion was investigated using a prototype high-pressure hydrogen injector (maximum 30 MPa). Experiments were carried out with a 2.2-liter 4-cylinder diesel engine equipped with a centrally mounted hydrogen injector, a toroidal shape combustion chamber, and a spark plug in the glow plug position. Furthermore this engine was modified to allow the supply of hydrogen to a single cylinder. By controlling both injection and spark timing, homogeneous and stratified combustion was studied. In addition, diffusive combustion used in combination with SI (i.e., spark assisted diffusive combustion) was investigated.

Result shows that stratified and diffusive combustion by high pressure direct injection greatly improves indicated thermal efficiency by approximately 3% compared with conventional homogeneous combustion. This advancement is derived from three reasons. 1) Stratified and diffusive combustion improves trade-off between cooling loss and degree of constant volume. 2) Pressure recovery effect by injection

close to TDC has a large advantage on thermal efficiency. 3) EGR is effective when it is combined with stratified and diffusive combustion.

Furthermore by suppressing jet penetration to reduce more cooling loss, a good indicated thermal efficiency for a small engine of 52% was achieved. Phenomenon was confirmed by CFD and visualization of in-cylinder combustion.

In addition, some valuable knowledge was derived that dehumidifying EGR increases specific heat ratio of the working gas, and improves thermal efficiency while reducing NO_x.

1. INTRODUCTION

Since oil resources are limited and some reports have stated that peak oil has already been reached, technology is being actively developed to respond to the need to adopt renewable energy sources in the future.

Electric vehicles (EVs) are regarded as highly efficient since many renewable energy sources, such as photovoltaic, solar thermal, and wind power can be harnessed as electric power. However, the energy density of batteries is low and there are still many issues to be resolved before electricity can be fully utilized as a power source for transportation.

In contrast, although hydrogen has lower portability and energy density than liquid fuels, it can be produced from a variety of renewable energy sources and efficiently obtained on an industrial scale by electrolysis. As a consequence of these and other merits, it is predicted that hydrogen could play a greater role in meeting society's energy needs in the mid- to long-term.

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Power sources that are capable of using hydrogen fuel include the fuel cell and the internal combustion engine. However, widespread use of fuel cells depends on the resolution of a number of issues such as cost and durability. In contrast, hydrogen internal combustion engines are based on mature technology and can therefore be realized at a comparatively lower cost. Gasoline-based hydrogen engines have limitations, but have already been put into practical use.

Some of the issues related to the use of hydrogen in an internal combustion engine are already known. For example, hydrogen engines have low thermal efficiency because of high cooling loss, and are difficult to operate at high loads because of backfire and an excess burning velocity⁽¹⁻²⁾. In recent years, direct injection has been researched to improve this issue^(3, 4, 5, 6, 7, 8), but combustion methods that enable both high efficiency and low NOx have yet to be studied in enough detail.

The research described in this paper examined methods of hydrogen combustion to achieve high efficiency and low NOx using a prototype high-pressure hydrogen injector (maximum 30 MPa). This research identified a means of achieving thermal efficiency close to that of a fuel cell (targeted indicated thermal efficiency: 55%) by developing stratified and diffusive combustion with high injection pressure. This paper also details the future directions and issues of this research.

2. TEST EQUIPMENT AND METHOD

Although lean burn, supercharging, increasing the expansion ratio, and reducing friction are effective measures to improve thermal efficiency, this research concentrated on utilizing characteristics particular to hydrogen combustion.

Diffusive combustion such as that utilized in diesel engines is considered to be an effective combustion method for increasing thermal efficiency. However, the properties of hydrogen make it more suitable for spark ignition (SI) and it is not well suited for compression ignition (CI). For this reason, this research mainly focused on diffusive combustion used in combination with SI (i.e., spark assisted diffusive combustion).

2.1. HIGH-PRESSURE HYDROGEN INJECTOR

To realize stratified and diffusive combustion, the required amount of hydrogen must be injected in an extremely short period of time close to top dead center (TDC) while overcoming the cylinder pressure. Therefore, the high-pressure hydrogen injector is the key technology for achieving this combustion. This research developed a

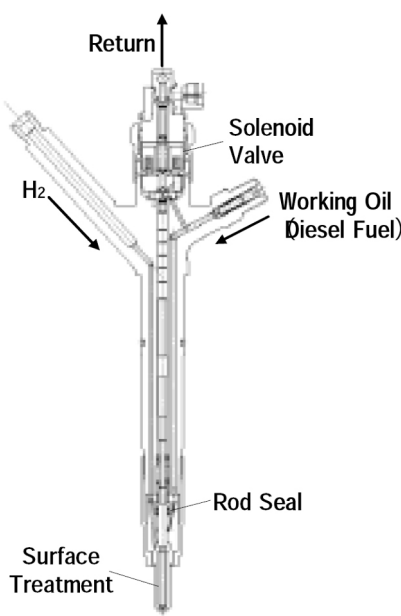


Fig. 1. Cross-section of Injector

prototype high-pressure hydrogen injector with a maximum injection pressure of 30 MPa as a testing tool. The injector is based on a mass-production diesel injector, but it is configured to supply hydrogen to the nozzle tip (Fig. 1). Hydraulic drive is used to increase airtightness at the nozzle seat, and the response was improved to enable multi- and high-flow injection (Table 1). In addition, two new technologies were incorporated into the injector: (1) surface hardening treatment and high-precision machining of the seat and dry sliding portions, and (2) a hydrogen rod seal at the sliding portion.

Table 1. Injector Specifications

Type	Hydraulic with Solenoid Valve
Injection Pressure	10~30MPa
Working Oil	Diesel Fuel, ~60MPa
Max Injection Quantity	300Nml/st (Equivalent to 90mm ³ /st Diesel Fuel)
Nozzle Hole	φ 0.43×6

A conventional hydraulic gas injector uses oil for lubrication or sealing, which means that oil is also injected with the fuel^(9, 10). In contrast, the new injector is capable of injecting hydrogen only. The concentration of exhaust emissions in the test was CO = approx. 0.01%, CO₂ = approx. 0.04%, and THC = approx. 15 ppm, which is a positive indication of the potential of pure hydrogen direct injection combustion.

2.2. TEST EQUIPMENT

The test engine was based on a 2.2-liter 4-cylinder mass-produced diesel engine, which was modified to allow the

supply of hydrogen to a single cylinder. The engine was provided with an independent one-cylinder intake/exhaust system separate from the other three cylinders and exhaust gas recirculation (EGR) was carried out. Table 2 shows the test engine specifications and Fig. 2 shows an outline of the combustion chamber. The piston cavity was configured to have a toroidal shape with central injection, and a spark plug was set in the glow plug position. All the results in this paper were obtained with the use of spark ignition. Tests were performed under multiple loads under the following conditions: engine speed = 2,000 rpm, natural aspiration (NA), intake throttle valve wide open.

Table 2. Engine Specifications

Engine Type	In-line 4-cylinder
Bore and Stroke	86×96
Displacement	557.6cc/cyl
Valve Train	4-valve DOHC
Compression Ratio	15.0~15.8
Swirl Ratio	2.3

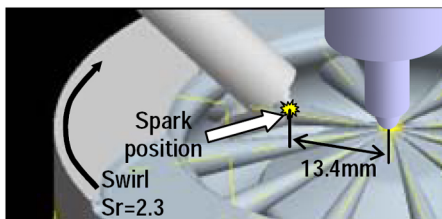


Fig. 2. Combustion Chamber and Gas Jet Arrangement

The hydrogen flow was measured by a coriolis mass flow rate gauge (CMF010 manufactured by Micro Motion). The indicated work was measured by an in-cylinder combustion pressure sensor (GH12D manufactured by AVL). The indicated thermal efficiency was then calculated from these two values.

3. TEST RESULTS AND CONSIDERATIONS

The sections below first describe the improvement effect of direct injection on thermal efficiency at low loads, followed by the reduction in NOx at medium to high loads through the use of high-pressure injection and EGR. The third section addresses a method for recovering the reduction in thermal efficiency caused by the use of EGR, and the final section covers an injection method that aims to reduce cooling loss.

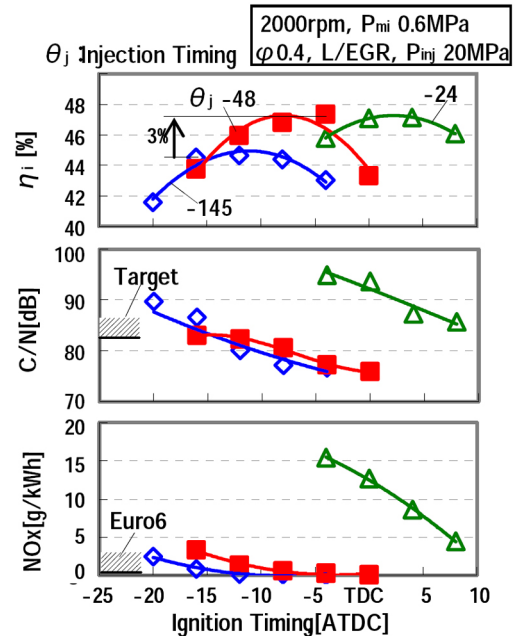


Fig. 3. Effect of Injection Timing on Combustion Characteristics

3.1. THERMAL EFFICIENCY IMPROVEMENT AT LOW TO MEDIUM LOADS BY DIRECT INJECTION

1. TEST RESULTS

In order to identify the basic properties of hydrogen, the influence of the injection and ignition timings at an equivalence ratio of $\phi 0.4$ was examined. Figure 3 shows the results. Compared with θ_j -145ATDC injection, which assumes homogenous SI combustion, the indicated thermal efficiency was greatly improved by approximately 3% by injection close to TDC. NOx and combustion noise worsened, but an appropriate injection timing would lower NOx to the levels stipulated by the Euro 6 regulations and reduce combustion noise. Figure 4 shows the combustion pressure at the optimum ignition timing (MBT). The closer the injection timing is to TDC, the higher the degree of constant volume of the combustion becomes. This is because narrowing the interval from injection to ignition increases the degree of stratification of the mixture and because combustion takes place in the strong turbulence produced by the injection.