

Efficiency and Emissions-Optimized Operating Strategy of a High-pressure Direct Injection Hydrogen Engine for Heavy-duty Trucks

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ABSTRACT

Hydrogen engines are required to provide high thermal efficiency and low nitrogen oxide (NO_x) emissions. There are many possible combinations of injection pressure, injection timing, ignition timing, lambda and EGR rate that can be used in a direct-injection system for achieving such performance. In this study, several different combinations of injection and ignition timings were classified as possible combustion regimes, and experiments were conducted to make clear the differences in combustion conditions attributable to these timings. Lambda and the EGR rate were also evaluated for achieving the desired performance, and indicated thermal efficiency of over 45% was obtained at IMEP of 0.95 MPa. It was found that a hydrogen engine with a high-pressure direct-injection system has a high potential for improving thermal efficiency and reducing NO_x emissions. Different engine management strategies involving the injection pressure, injection timing, ignition timing, lambda and the EGR rate were also evaluated under a Japanese emissions test cycle. Based on the experimental results, NO_x emissions and fuel economy were estimated by simulation for a heavy-duty vehicle fitted with a 6-cylinder DI hydrogen engine. An original simulation program has been developed and a simulation database has been created based on experiments conducted with a single-cylinder engine. Finally, the paper projects the potential of an engine management strategy for obtaining high output power and energy efficiency equal to the baseline diesel vehicle while also attaining low NO_x emissions of 0.5 g/kWh under the emissions test cycle.

INTRODUCTION

Among the efforts mounted in recent years to reduce carbon dioxide (CO₂) emissions, hydrogen engines

contain any CO₂. One of the notable features of direct-injection hydrogen engines is that backfire can be avoided. It is expected that a shortcut to the early use of hydrogen fuel can be achieved by designing hydrogen engines with the same basic structure as that of existing internal combustion engines. Moreover, it has been reported that a suitable combination of injection and ignition timings or optimized fuel nozzle design can result in high thermal efficiency [1]-[3] as well as the potential for low nitrogen oxide (NO_x) emissions under some test mode for measuring exhaust emissions on board [4]-[6]. However, many different combinations of injection pressure, injection timing and ignition timing are possible with a direct-injection system. In addition, when the effects of different engine operating conditions are also considered, it is not easy to ascertain the combustion characteristics of hydrogen fuel, and the actual characteristics are still not clearly understood. In this study, a single-cylinder test engine fitted with a fuel injector producing a maximum injection pressure of 20 MPa was used to examine three combustion regimes, which were classified primarily on the basis of the injection timing and ignition timing, among the many different parameter combinations possible. The experimental results revealed that each combustion regime showed different combustion characteristics depending on the operating conditions set for the engine speed and load. The effect of the fuel injection pressure on thermal efficiency and the effect of exhaust gas recirculation (EGR) on reducing NO_x emissions were also confirmed at the same time. Moreover, a trace emissions simulation method [4] was used to estimate in-vehicle emissions performance under JE05 test mode conditions, based on the emissions levels measured during steady-state operation of the single-cylinder test engine. The results suggest that optimized management of the above-mentioned control parameters was effective in reducing test mode emissions.

SINGLE CYLINDER ENGINE EXPERIMENTS

ENGINE SPECIFICATIONS

The specifications of the single-cylinder test engine used in the experiments are given in Table 1. The configuration of the combustion chamber and the positional relationship between the injector and the spark plug are shown in Fig. 1. The combustion chamber had a bowl shape, and a nine-hole injector nozzle was used to supply the fuel with the aim of dispersing it throughout the bowl. The ignition position was located near the injector nozzle holes in the center of the bowl as a result of extending the central electrode of the spark plug. A high-pressure hydrogen direct-injection system was adopted using an injector with a maximum injection pressure of 20 MPa. This level of injection pressure has been set as a development target for achieving a higher injection rate.[1] The idea is to avoid a decline in thermal efficiency by supplying the fuel and completing combustion in the first half of the expansion stroke under high-speed engine operation. Notable features of this direct-injection system include the ability to inject fuel at high pressures up to 20 MPa and its high-speed response. This performance is achieved by using a common-rail hydraulic-driven needle injector. The system is capable of injecting the maximum required quantity of fuel into the combustion chamber in an injection interval of 30 crank angle (CA) degrees at 3000 rpm. The injection timing and duration are controlled by using the common rail system to regulate the spill quantity and timing of the fluid supplied to the injector. The high-speed response also facilitates multiple-stage injection (Table 2), [7].

Table 1 Specifications of single-cylinder engine

Item	Specification
Engine Displacement	1054 mL
Bore x Stroke	108mm x 115mm
Combustion Chamber	Bowl
No. of Valves	2 valves
Cooling System	Water Cooled
Compression Ratio	13:1
Ignition System	Spark Ignition

Table 2 Specifications of high-pressure injector system

Items	Specification
Needle Type	Multi Hole Nozzle Oil Pressure Driven & Back Pressure Spill Control
Max. Oil Pressure	: 120 MPa
Max. Inj. Press.	: 20 MPa
Max. Inj. Rate	: 400 Nml/st @30 deg CA, 3000 rpm

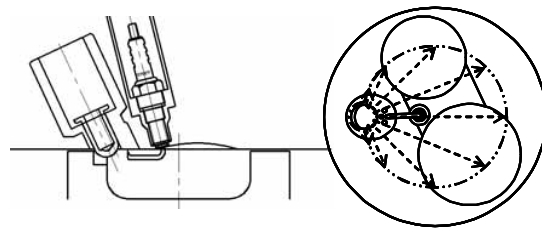


Fig. 1 Combustion chamber configuration of the single cylinder engine

Hydrogen fuel was introduced into the injector after reducing the fuel pressure supplied from a high-pressure cylinder having a maximum pressure of 40 MPa. The fuel flow rate was measured with a hot-wire mass flow-meter (F-133S, OVAL Corp.). The intake air quantity was measured with a laminar flow-meter (LFE-25B, SOKKEN Co., Ltd.). The fuel injection timing, injection duration and ignition timing were set using a control system that enabled these operating parameters to be set arbitrarily in reference to the engine crank angle. A Kistler water-cooled piezoelectric pressure transducer was used to measure the cylinder pressure for use in analyzing combustion characteristics. The hydrogen concentration in the exhaust was measured with a Horiba MEXA-9100 gas analyzer.

EXPERIMENTAL RESULTS AND DISCUSSION

Classification of combustion regimes according to combinations of injection timing and ignition timing

A direct-injection hydrogen engine capable of high injection rates like the high-pressure injection used in this study allows a large degree of freedom for setting the injection timing. There is an almost indefinite amount of possible combinations of injection and ignition timings, for optimizing thermal efficiency, power output, NOx emissions and other attributes. As a result of attempting to operate the test engine over the widest possible range of injection timing and ignition timing combinations, it was preliminarily found that injection and ignition timings could be broadly classified under the three types of specifications noted below, taking into consideration combustion stability. The results are shown in Fig. 2, where the injection timing is shown along the horizontal axis and the ignition timing is shown along the vertical axis. It is seen that the regions where combustion is feasible can be broadly divided into three zones. The combinations of injection timing and ignition timing corresponding to these three zones were classified as the three combustion regimes denoted below as a, b and c. The relationship between each combustion regime and combustion characteristics, thermal efficiency, emissions characteristics and other aspects was then investigated experimentally (Fig. 3).

a: Early injection and premixed mixture ignition (EI-PMi)

Fuel injection early in the compression stroke and ignition of a homogeneous mixture

b: Late injection and plume head ignition (LI-PHi)

Fuel injection late in the compression stroke and ignition in the first half of the injection process

c: Late injection and plume tail ignition (LI-PTi)

Fuel injection late in the compression stroke and ignition in the second half of the injection process.

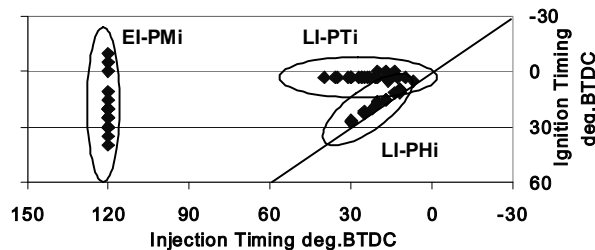


Fig. 2 Distributed operating regions obtained with different combinations of injection timing and ignition timing

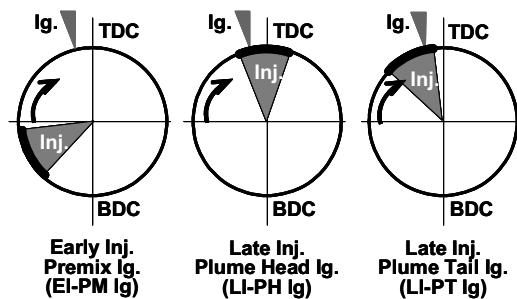


Fig. 3 Combinations of injection and ignition timing for controlling mixture formation

Combustion characteristics and performance under low-speed, low-load conditions

The effect of the injection timing and ignition timing on the indicated thermal efficiency η_i and NOx emissions obtained with each of the three combustion regimes classified under typical low-load operating conditions (engine speed: 1000 rpm; indicated mean effective pressure P_i : 0.27 MPa). Figure 4 shows the results obtained for η_i and the NOx emissions level in relation to the injection timing.

The EI-PMi regime was characterized by zero NOx emissions irrespective of the ignition timing. This indicates that a nearly homogeneous mixture was obtained with this regime in which the hydrogen fuel and

air were mixed in the interval from hydrogen injection to ignition. Both of the late fuel injection regimes (LI-PHi and LI-PTi) emitted NOx. The results show that NOx formation tended to increase as either the ignition timing or the injection timing was advanced.

The same data are plotted in Fig. 5 where η_i is shown along the horizontal axis and the NOx emissions level along the vertical axis. The results indicate that higher η_i and lower NOx, which tend to be incompatible characteristics, were obtained with combinations of injection timing and ignition timing closer to the origin (lower left corner).

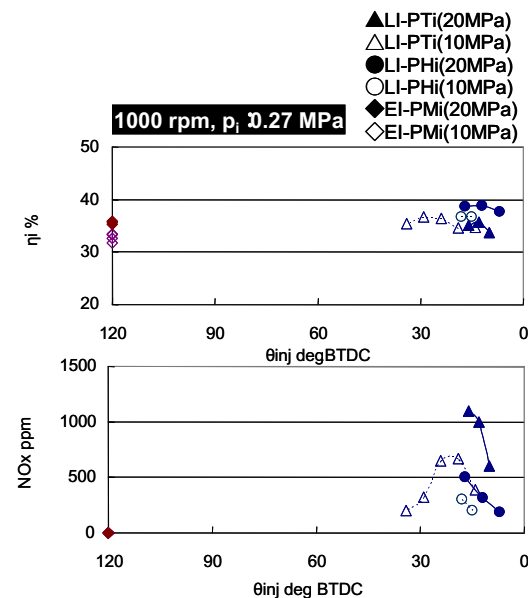


Fig. 4 Effect of θ_{inj} on η_i and NOx emissions

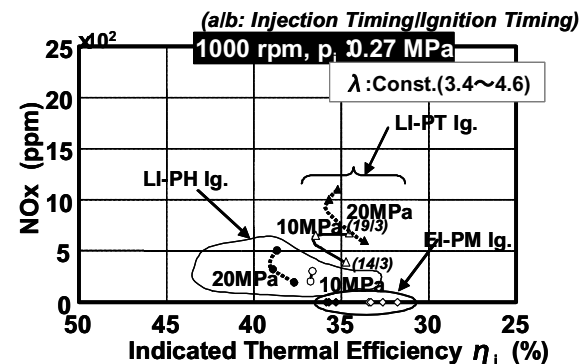


Fig. 5 Characteristics of η_i and NOx emissions for combinations of SI and fuel injection

Combustion characteristics and performance under high-speed, high-load conditions

The effect of the injection timing and ignition timing on the indicated thermal efficiency η_i and NOx emissions obtained with each of the three combustion regimes was