

Hydrogen DI Dual Zone Combustion System

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ABSTRACT

Internal combustion (IC) engines fueled by hydrogen are among the most efficient means of converting chemical energy to mechanical work. The exhaust has near-zero carbon-based emissions, and the engines can be operated in a manner in which pollutants are minimal. In addition, in automotive applications, hydrogen engines have the potential for efficiencies higher than fuel cells.[1] In addition, hydrogen engines are likely to have a small increase in engine costs compared to conventionally fueled engines. However, there are challenges to using hydrogen in IC engines. In particular, efficient combustion of hydrogen in engines produces nitrogen oxides (NO_x) that generally cannot be treated with conventional three-way catalysts.

This work presents the results of experiments which consider changes in direct injection hydrogen engine design to improve engine performance, consisting primarily of engine efficiency and NO_x emissions. Two cylinder head configurations and two fuel injector designs were considered. One cylinder head used central spark ignition and the other used dual side spark ignition. One fuel injector used a symmetric geometry of five holes (5H, a central hole with 4 holes arranged at cardinal compass points around the central hole), and the other used a six hole geometry with three holes on each side of the nozzle (3+3H) aimed towards the spark plug locations of the dual side ignition cylinder head ($\beta=0^\circ$) and aimed perpendicular to the axis between the two ignition locations ($\beta=90^\circ$). Two engine speeds were tested, 1500 and 3000 rpm, with constant equivalence ratio of $\phi = 0.4$. The new dual side ignition cylinder head design, when coupled with the 3+3H $\beta=0^\circ$ injector, produced 47.7% net indicated thermal efficiency (ITE) while producing only 51 ppm of NO_x. The results are discussed in terms of fuel/air mixing times, fuel/air stratification and heat transfer losses.

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INTRODUCTION

Although the efficiencies of hydrogen engines tested have been promising [2], the high fuel costs of operating an engine on hydrogen warrant attempts to continue to reduce the combustion and heat transfer losses. Several studies have been conducted to explore the effects of different combustion chamber geometries on improving hydrogen engine performance, including fuel injector nozzle geometry and location, piston surface, and spark plug location [3, 4, 5, 6] For example, Kim et al. [c] tested four nozzles, including one nozzle intended to induce swirl in the chamber. Metal engine tests and optical Schlieren tests were conducted, and the full-open nozzle was shown to have superior efficiency and

combustion stability. Wallner et al. [c] at Argonne National Laboratory (ANL) tested two nozzles in central and side locations. The best efficiency was seen with the 5 hole injector when located in the side of the combustion chamber with the nozzles oriented towards the spark plug. Unfortunately, at those conditions, NO_x emissions exceeded 150 ppm, which would likely require aftertreatment to comply with emissions regulations.

Based on these previous studies, it was hypothesized that using two ignition sites, on the side of the combustion chamber, would help reduce the losses due to combustion delay and improve engine performance. Furthermore, a dedicated injector, designed to direct fuel towards the spark plugs while entraining air, was designed and tested in this



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study. The objective of the current work was to quantify the effects of the new engine geometry on H_2 engine performance, particularly in terms of engine power, efficiency and emissions. The results for the dual-side-ignition cylinder head and the dual-zone injector (a six hole injector with three holes targeted to each spark plug) are introduced and contrasted with those of the conventional cylinder head and baseline five hole fuel injector.

EXPERIMENTAL SETUP AND APPROACH

All tests were conducted at Ford Motor Company on a 592 cm^3 single cylinder engine. The experimental facility is described in detail in [7]. Briefly, direct in-cylinder injectors metered >99.9% pure hydrogen at 110 bar into the cylinder.

Cylinder pressure was measured with an AVL GU21C cylinder pressure transducer. Coupled with an optical rotary encoder, indicated mean effective pressure (IMEP) calculations were obtained with an expected accuracy of 1% of measurement. For all tests, 300 engine cycles were acquired and averaged. NO_x was measured with a Horiba MEXA-7100 dual-range (100 ppm and 10000 ppm) system; error was estimated to be less than 0.87% of the scale used.

A 300 horsepower A/C dynamometer was used to control engine speed and absorbed torque. Fuel flow was measured with a coriolis flow meter with expected error of 1% of measurement. Intake air was metered by pressurizing air and directing the flow through choked nozzles. Pulsations resulting from single-cylinder operation were dampened by flowing the intake and exhaust gases through drums of approximately 25 liters each. Some of the major engine design specifications are shown in Table 1.

Table 1. Engine dimensions and specifications

Bore	89	mm
Stroke	95	mm
Cylinder Displacement	592	cm^3
Connecting Rod Length	169.1	mm
Intake Valve Diameter	35	mm
Exhaust Valve Diameter	30	mm
Intake Duration	230	deg
Intake Centerline	100	deg ATDC
Exhaust Duration	230	deg
Exhaust Centerline	105	deg BTDC
Dual Ignition Compression Ratio	12.5:1	
Single Ignition Compression Ratio	11.6:1	

The cylinder heads used for these experiments are shown in Table 2. Both cylinder heads used ports designed to minimize charge motion. One cylinder head used central spark ignition and the other used dual side spark ignition.

Table 2. Cylinder heads and injectors tested

		
Name	Single Central Ignition Head	Dual Side Ignition Head
Injector Loc.	Central	Central
Spark Loc.	Central	Dual Side

The H_2 fuel injectors, developed by Westport Innovations, were chosen based on superior durability and efficiency in preliminary testing. Details on the challenges of injector design for direct injection of hydrogen can be found in [8]. The nozzles considered in this study are shown in Table 3. The baseline fuel injector used a symmetric geometry of five holes (5H) with a central hole with 4 holes arranged at cardinal compass points around the central hole. The other fuel injector used a six hole geometry with three holes on each side of the nozzle aimed towards the spark plug locations of the dual side ignition cylinder head (3+3). The fuel injectors were tested in both cylinder head configurations.

Table 3. Fuel injector nozzle designs tested.

		
Pattern	5H	3+3H
Spray Angle (deg)	0/35	45/70
Nozzle Diameter (mm)	0.597	0.545
Nozzle Area (mm^2)	0.280	0.233
Total Flow Area (mm^2)	1.4	1.4

The effect of changing the H_2 /air mixing time was investigated by incrementally decreasing the mixing time allowed between fuel injection and ignition, which was characterized by the timing of the start of injection (SOI). The equivalence ratio was fixed for the experiments at $\phi = 0.4$ in order to maximize efficiency, minimize NO_x emissions, maintain reasonable pressure rise rates, and produce a moderate engine output (6.5-7.2 bar), based on previous work [7]. To obtain $\phi = 0.4$, both injectors required a commanded injection duration of approximately 23° CA at 3000 RPM, and 11.5° CA at 1500 RPM. Spark timing was

then varied to maximize the observed IMEP (MBT). For all points shown, 300 cycles of data was taken and averaged.

EXPERIMENTAL RESULTS AND DISCUSSION: INJECTOR AND CYLINDER HEAD DESIGN

Figure 1 compares the fuel consumption and NO_x production of the four cylinder head and injector configurations. The error bars presented in Figure 1 represent the expected measurement error for each engine configuration and are presented for one data point in Figure 1 for clarity. The following bulleted lists summarize the observations for the four configurations of cylinder heads and fuel injectors. The format of the bullets corresponds to the symbols used in Figure 1 and throughout this work. All 3+3H tests in this section were conducted with the fuel injector oriented to direct the H₂ towards the spark plugs in the dual side ignition cylinder head or $\beta=0^\circ$. All results presented in this section were for an engine speed of 3000 rpm.

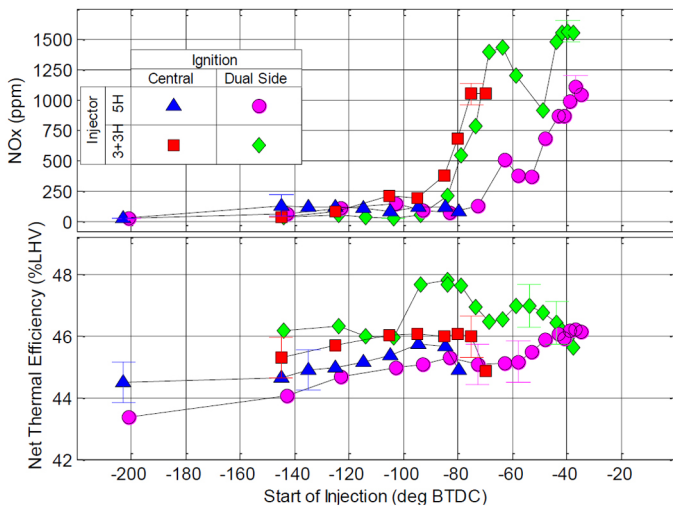


Figure 1. Indicated thermal efficiency and NO_x emissions as a function of SOI.

- When the baseline 5H injector was paired with the baseline central ignition cylinder head, the best thermal efficiency observed was 45.7% at an SOI timing of 95° before top dead center (BTDC).
- The NO_x production at the maximum efficiency condition was 115 ppm.
- As SOI was advanced, more mixing time (yielding presumably more homogenous combustion conditions) decreased NO_x, but also decreased efficiency.
- When injection timing was delayed to less than 80° BTDC, combustion stability suffered, specific fuel consumption increased, and data were not taken.
- When the 3+3H injector (at $\beta=0^\circ$) was paired with the baseline central ignition cylinder head, the maximum

efficiency observed increased to 46.1% at an SOI timing of 95° BTDC.

- The NO_x production at the maximum efficiency condition was 190 ppm.
- The range of stable combustion was increased compared to the baseline head/5H results and data were acquired until SOI reached 70° BTDC.
- When the 5H injector was paired with the new dual-side-ignition head, the maximum observed efficiency increased to 46.2% at an SOI timing of 37° BTDC.
- At this highly stratified condition, there was a substantial NO_x penalty, exceeding 1100 ppm.
- Stability improved at all points with this combination of fuel injector and cylinder head, and data were acquired until the SOI timing reached 35° BTDC.
- With the exception of the SOI leading to the maximum observed efficiency, most of the earlier injection timings led to thermal efficiencies which were lower than either of the previous two injector/head configurations.
- When the 3+3 injector (at $\beta=0^\circ$) was paired with the dual plug cylinder head, efficiency improved to 47.8% at SOI of 83° BTDC.
- The NO_x production at the maximum efficiency condition was 208 ppm.
- Increasing the mixing time slightly to an SOI of 94° BTDC decreased efficiency to 47.7% but also decreased NO_x to 51 ppm.
- For this injector/head configuration, local maxima and minima were observed for efficiency and NO_x emissions throughout the range of SOI timings.

Figure 2 presents the NO_x emissions as a function of fuel consumption for the data of Figure 1. When compared to the baseline central-ignition/5H pairing, the dual-side-ignition/5H and central-ignition/3+3H pairings made minor improvements in fuel consumption with substantial NO_x penalties. When the 3+3H was paired with the dual-side-ignition head, improvements were made in both fuel consumption and NO_x simultaneously. For example, at 47.7% ITE, only 51 ppm of NO_x was produced.