Combustion Analysis of Various Speed on Hydrogen (H_2) in a Direct Injection Diesel Engine Modified to operate as a Low Heat Rejection (LHR)

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Abstract

The feasibility of using hydrogen as the sole fuel in a direct injection diesel engine was investigated. An air cooled single cylinder diesel engine was modified to operate as a low-heat-rejection engine for this study. Partially stabilized zirconia (PSZ) ceramic parts were used to shield the combustion space of the engine. Using a compression ratio of 17.9:1 and motoring the test engine at 2100 rpm, a maximum compression temperature of approximately 900 K was achieved. Under these operating conditions, all lubricants tested were found to burn. Lowering the speed to 1450 rpm and the compression ratio to 17.1, lubricant combustion and hot spots were successfully eliminated. The maximum compression temperature, when compression ignition of hydrogen was tried, was in the 800 K range. The corresponding ceramic surface temperature was estimated to reach 600-700 K. Only sporadic compression ignition of hydrogen was achievable.

Key words: *Hydrogen, Compression Ignition Engine, Low heat Rejection, Compression Ratios.*

1. Introduction

The transportation sector causes a major part of the greenhouse gas emissions worldwide, but nowadays, sustainability and innovation in the automotive industry are based on new technologies [1], especially for internal combustion engines, which have an important place in the transportation field [2]. Furthermore, at the C40 Mayors Summit in Ciudad de Mexico held in 2016, a possible solution to the increased pollution in a few capitals (Paris, Athens, and Ciudad de Mexico) was considered to be the elimination of the automotive diesel engine by the year 2025[3]. It is remarked that hydrogen has good combustion properties, qualifying it as the cleanest fuel for ICEs and enabling high combustion efficiencies compared to other alternative fuels [4]. Hydrogen is an easily flammable gas, is inodorous, insipid, and colorless, and is found in nature as a diatomic molecule, H2. Hydrogen is the lightest chemical element and is also the most prevalent element in the universe. Takahashi [17] found that a minimum ignition temperature of 980 K was required in order to keep the ignition delay period to 2 ms. He based his finding on results which he obtained using a shock-tube to generate the high temperatures. He also concluded that it is difficult to apply hydrogen to fuel existing production diesel engines. On the contrary, Ikegami et al. [18] concluded that diesel operation with hydrogen injection was attainable. They used a conventional naturally aspirated divided chamber engine without resorting to a very high compression ratio. However, their findings were criticized by Homan and co-workers, who suggested that either the presence of minute quantities of engine oil or a hot spot in the combustion chamber had initiated hydrogen ignition. In a subsequent study, Ikegami et al. [19] stated that in their initial study, the injector was leaking hydrogen in a double injection system to achieve compression ignition. This fuel injection schedule apparently allowed for longer reaction time. A swirl chamber engine with a compression ratio of 18.6 was used. Engine coolant temperature was maintained at 90°C (363 K) and the engine was motored at 500 and 1000 rpm. Homan et al. [20] Used a diesel engine and fuel injector similar to those used in Ref. [19] to investigate compression ignition of hydrogen. Contrary to the findings reported in Ref. [19], they failed to achieve compression ignition even though their attempts were carried out at compression ratios as high as 29. Welch and Wallace [11] used an air cooled Lister ST1 single cylinder four-stroke diesel engine to investigate engine performance of a hydrogen-fuelled direct injection diesel. However, they had to install a glow plug to get ignition. It is clear from past research that compression temperature plays a controlling role on hydrogen ignition in diesel engines. Until the present, various techniques employed to increase the compression temperature of these engines had failed to achieve auto-ignition of hydrogen. But, with the advancement made in ceramic materials, it was felt that by installing some ceramic parts strategically into the combustion chamber of an engine, its maximum compression temperature can be increased above the auto-ignition temperature of hydro- gen. If this proved to be successful, it could eliminate the need to equip these engines with spark or glow plug systems. Another advantage is that the compression ratio of such an engine need not be increased beyond their design values. The objective of the present study was to investigate compression ignition of injected gaseous hydrogen and its related problems in a production engine which was modified to operate in a low-heat-rejection mode. The accelerated depletion of oil reserves highlights the necessity of alternative fuels, especially from durable and renewable resources, such as hydrogen, which may be produced from plants [5]. While this paper presents some challenges, its main objective is to study the increase in the energetic performance of automotive diesel engines through the addition of hydrogen to diesel fuel. On one hand, hydrogen has a lower energy density compared to diesel, so an adequate design of fueling systems must be developed, in order to keep the engine power constant. On the other hand, the inferior auto ignition properties of hydrogen necessitate the application of methods which are specific to hydrogen fueling. So our main objective, i.e., measuring the increase in the energetic performance of automotive diesel engines by the addition of hydrogen to the fuel, requires the use of a fueling method which is easy to apply and suitable for all diesel engines. The diesel–gas method, which is considered easy to apply to old or new diesel engine designs, was used as the fueling method. This paper presents some experimental results of hydrogen use in a diesel engine. The authors studied the influence of the hydrogen cyclic dose on the energetic and combustion performance of the engine. The novelty aspect of this research is its determination of the optimal correlation among engine operating regime, fuel cyclic dose, combustion parameters and pollutant emissions, in order to apply these data to a modern diesel engine.

2. Materials and Methods

2.1 Low Heat Rejection Engine

In diesel engines, increasing the combustion temperature improves efficiency and reduces emissions. This necessitates the use of heat-resistant materials for the combustion chamber components. Adding a ceramic coating to these components can improve their high-temperature resistance. It has been proven that alternative fuels emit less pollution when burned at higher temperatures. In addition, the coating acts as a thermal barrier to reduce the amount of heat that is transmitted through the combustion chamber [5]. In internal combustion engines, only a tiny portion of the total energy from burning is transformed into usable energy. In order to preserve engine parts from overheating, friction and exhaust, more than half of this energy is lost through the cooling system. By reducing the specified losses, the engine's useful work may be increased most effectively. A material with poor thermal conductivity and strong thermal resistance under extreme temperatures should be used or coated on sections of the combustion chamber to achieve this. Recently, ceramic-coated engine components have been utilized. Study's goal was to improve the engine's performance and make the engine parts more resistant to wear and corrosion. Plasma spray coating is used to provide heat barrier coatings to cylinder heads, pistons, and valves. Ceramic coatings protect these parts against wear, friction, heat, corrosion, and oxidation. Using low-quality fuel was achievable because the combustion chamber temperature was greater in the ceramic coated engines than in the uncoated engines. Dessication will also cause a decrease in the amount of energy that the cooling system removes, which will lead to a greater temperature in the combustion chamber following compression [6].

Plasma spray coating was used to coated the cylinder head, valve, and piston of the test engine with 0.5 mm thick zirconia.

2.2 Coating Process

Plasma spraying is the spraying of molten or heat softened material onto a surface in order to produce a coating or protection against corrosion. Zuerst wird an extremely high temperature plasma flame used to rapidly heat and accelerate zirconia powder to a high speed. After impacting the substrate, the hot substance rapidly cools, leaving behind a coating. As a heat source, an electric arc was maintained in the nozzle of the plasma spraying method. Inert gases are heated to a very high degree by the arc. The gas molecules are dissociated and ionized as a result of the high temperature. Gas volume increases dramatically when heated to high temperatures, causing it to flow at an extremely high velocity (plasma jet). Using a carrier gas, a powdered coating substance is pumped into the feed unit from the feed unit.

These particles melt and adhere to the surface of the treated base material as a protective layer when heated. It is shown in Figure 1 that a low heat rejection engine uses zirconia-coated piston, cylinder head and valve components.

Figure 1. Zirconium coated piston, cylinder head and valves

Table 1 Properties of Hydrogen and diesel

Properties	Hydrogen	Diesel
Density(kg/m^3, at 20°C)	0.08375	820
Flash point(°C)	Flammable gas	68
Auto ignition temperature(°C)	560	300-340
Lower heating value(MJ/kg)	119.96	43
Cetane number	53.2	42
Vapor pressure (kPa at 38°C)	11.9	0.34
Latent heat of vaporization (kJ/kg)	455	620

3. Experimental setup

Figures 2 depict the experimental setup utilized in this study a single-cylinder four-stroke engine with a 17.5:1 compression ratio and 4.4 kW at 1500 rpm, connected to a variable-resistance generator. There was a 200bar injector rating and a static injection timing of 23° BTDC on the engine. Checked gasoline level in tank, water flow, and oil level in engine oil sump before starting the engine. After starting the engine, it was warmed up. All engines ran at their rated speeds. Current and voltage measurements were used to determine the engine's power output. To measure the cooling water temperature, a thermocouple with a digital temperature indication was utilized. One of the piezoelectric sensors measured the pressure in the tank. QROTECH exhaust gas analyzer analyzed CO, NOx, and HC emissions. We utilized a TI Diesel Tune smoke meter to measure the amount of smoke. No load and full load loads were used in the studies.

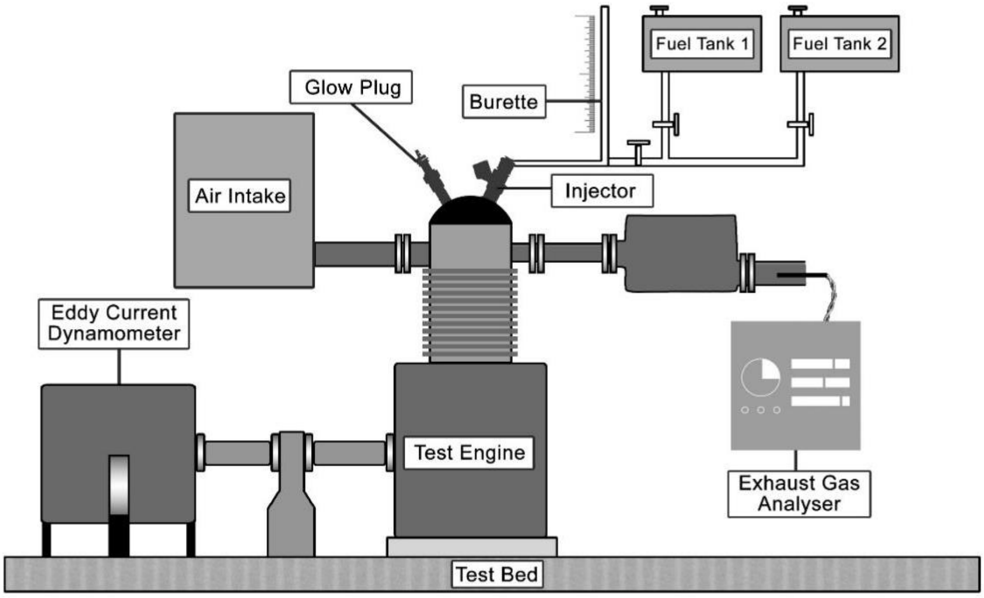

Figure 2. Schematic view of experimental setup

4. Results and Discussions

All hydrogen compression ignition tests were carried out at 1450rpm (nominal) with compression ratio of 17.1. Based on pressure curves obtained by motoring the engine, the calculated maximum compression temperature, without hydrogen injection, was in the 800 K range. This temperature was lowered by less than 5% when hydrogen at room temperature was injected. Comparison of pressure curves under identical test conditions, but with and without hydrogen injection and in the absence of ignition, supported this estimation. Under these operating conditions, engine lubricating oil combustion and hot spots resulting from lubricating oil deposits were successfully eliminated. This was verified by monitoring the pressure curve during motoring and by periodic removal of engine head for visual inspection. Further confirmation was obtained by a series of high temperature branch tests on the lubricant using a heated surface to duplicate lubricant deposit formations during motoring. Even though a maximum compression temperature as high as 900 K was achieved by motoring the Lister engine at 2100 rpm using a compression ratio of 17.9, a still higher temperature was considered attainable if the original stock engine compression ratio of 19.4 was restored. This was not done because lubricant combustion had already imposed an upper limit on the compression temperature. Safety considerations prevented the tests from being carried out at 2100 rpm when gaseous hydrogen was to be injected. Many hydrogen compression ignition experiments were carried out. Only sporadic ignition was achieved. Some of the experimental curves are included here. Figure 4 shows the cylinder pressure curve as a function of crank angle. Ignition was at 3° before TDC. The portion of pressure rise curve after ignition showed steps. The break just after TDC was believed to be the result of temporary fuel depletion after combustion had started. The breaks near the top of the curve were believed to have been caused by a combination of:

(1) The existence of pressure oscillations during this period in the combustion stroke, and
(2) The slow sampling rate of the data acquisition system.
Maximum pressure occurred approximately 7 crank angle degrees after TDC. The jerk pump rack setting was at 8.25. Engine speed was 1450 rpm. Figure 5 shows a second pressure curve which was obtained under identical experimental conditions as Fig. 4. However, ignition occurred approximately 5 ° after TDC, indicating a longer ignition delay. Maximum cylinder pressure was significantly lower, by about 16%, and occurred much later during the expansion stroke. Figure 6 shows a pressure curve which was obtained with a rack setting at 8.50. The engine speed was 1479rpm. Ignition occurred approximately 7 ° before TDC.
The pressure rise portion of this curve is better than that of Fig. 4, suggesting higher power output, even though the power output cannot be measured with the present set-up. The breaks near the top of the pressure curve were believed to have been caused by the same two factors as in Fig. 4 above. Figure 7 is a sample of the pressure curve, when only one channel was used in the data acquisition system to capture the cylinder pressure information. The rack setting was 8 and the engine speed was 1320 rpm. The sampling rate is slower in order to record more consec- utive cycles. Much can be learnt from these experimental results.

(l) Compression ignition of hydrogen was sporadic at calculated maximum compression temperature of around 800 K. Hydrogen injection lowered the mixture temperature by less than an estimated 5%. Since ignition in these cycles occurred very close to TDC, the compression ignition temperature of hydrogen in these experiments was near to the calculated maximum but below the auto- ignition temperature of 844 K. These results seem to support the findings by Homan et al. [20], who failed to ignite hydrogen in a diesel engine with a compression ratio as high as 29.

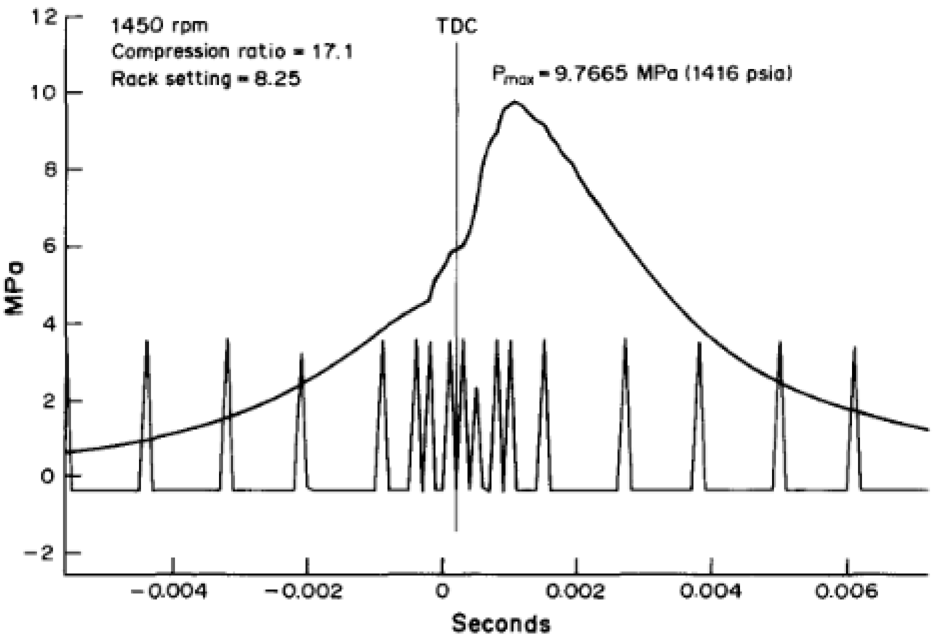

Figure 4.Cylinder pressure---compression ignition of hydrogen. 1450 rpm; Rack Setting = 8.25.

(2) Ignition delay varied significantly from cycle to cycle under identical experimental conditions. Even though the successful compression ignition results were within 1 ms of Takahashi's suggested ignition delay o f 2 ms at 980°K, the start o f ignition could be before or after TDC. For power generation, this is unacceptable.

(3) Cylinder pressure rise rate can be controlled by hydrogen injection rate. Because of the high flame propagation speed in combustible hydrogen/air mixtures, Karim's theoretical investigation showed rapid pressure rise during compression of such homogeneous mixtures when the temperature reached 550 K. However, in the current experiments, this undesirable phenomenon was suppressed successfully using hydrogen injection rate.

(4) Engine power output can be regulated by gaseous hydrogen injection duration. This was demonstrated experimentally to be feasible by adjusting the jerk pump rack setting. An electronically controlled, programmable and fast acting high pressure gaseous hydrogen injector would be needed.

(5) Sporadic compression ignition of hydrogen was achieved using arbitrarily chosen high cranking speed and low-heat-rejection engine cooling configuration. These are impractical for production engines. Therefore, spark ignition would be m o r e suitable to control timing and to insure ignition.

High temperature lubricants need to be developed for low - heat - rejection engines. Presently available lubricants cannot withstand the high combustion chamber surface temperature resulting from continues running

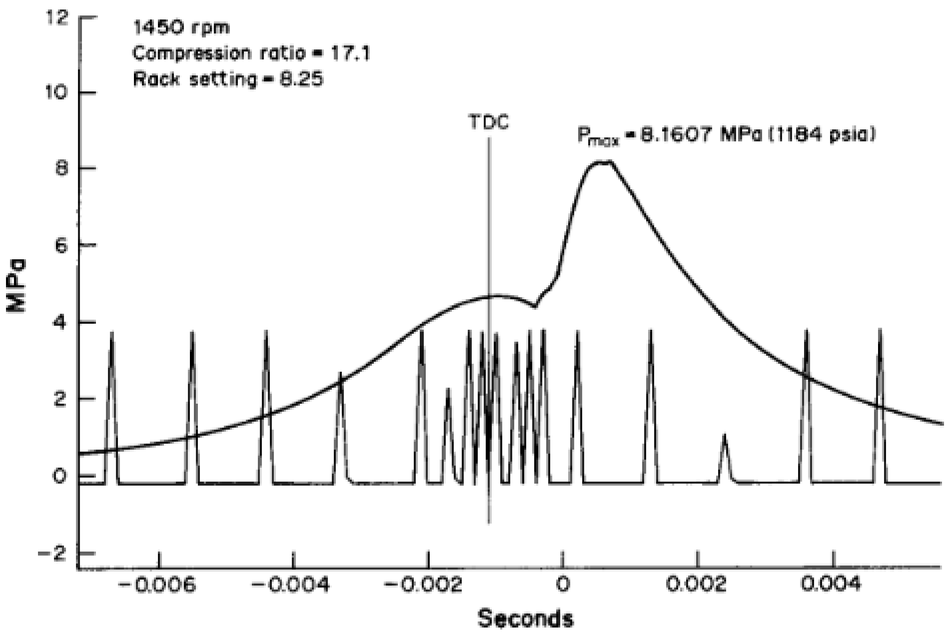

Figure 5 Cylinder pressure--compression ignition of hydrogen. 1450 rpm; Rack Setting = 8.25.

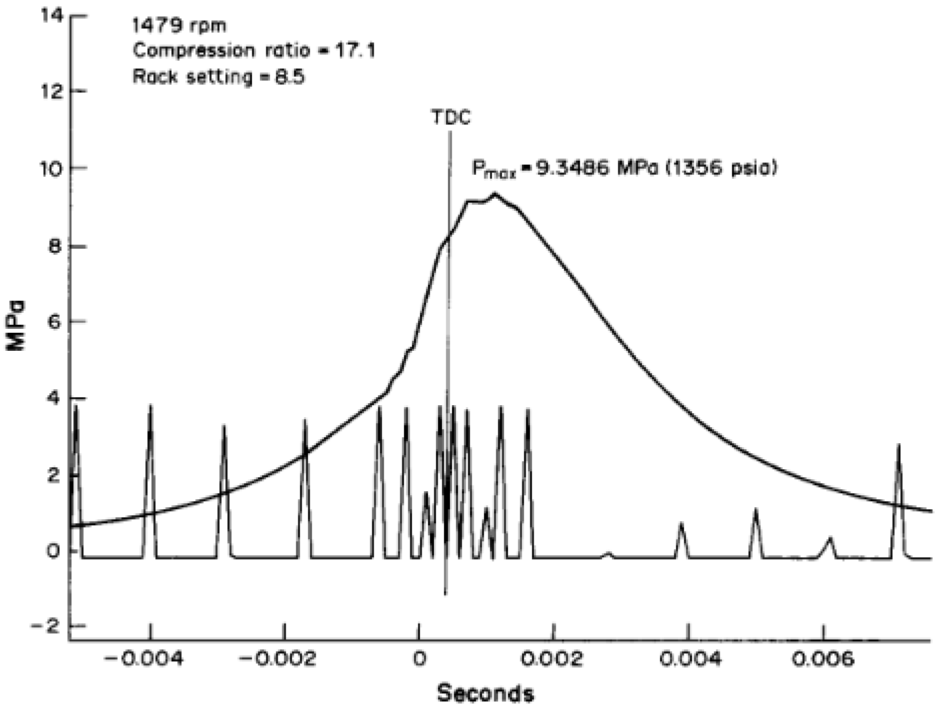

Fig. 6. Cylinder pressure---compression ignition of hydrogen. 1479 rpm; Rack Setting = 8.5.

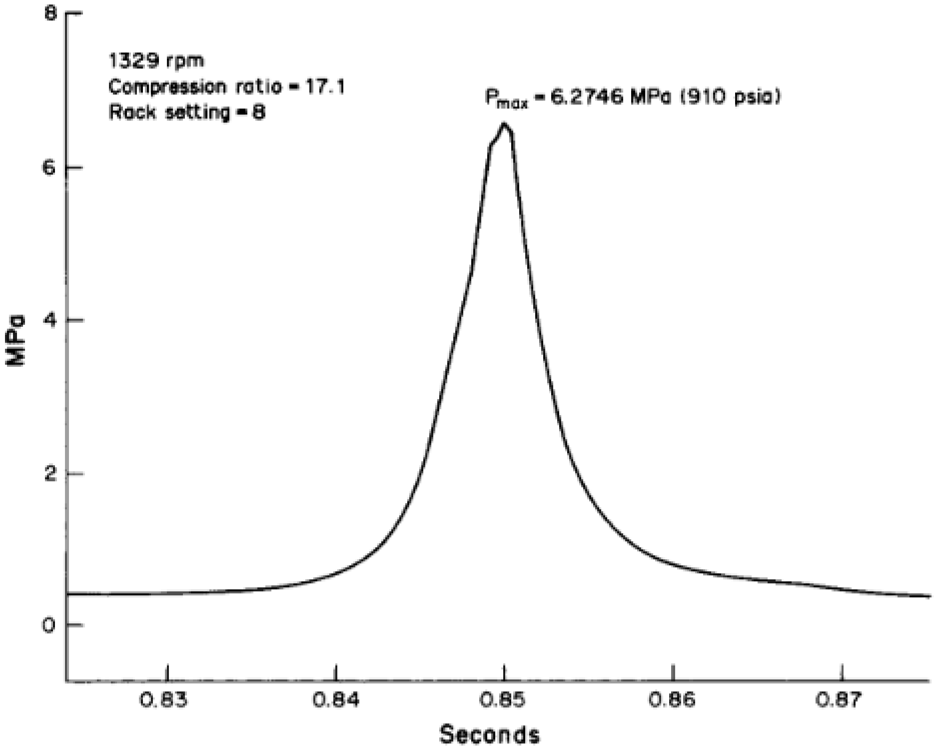

Fig. 7. Cylinder pressure---compression ignition of hydrogen. 1329 rpm; Rack Setting = 8.0

Conclusion

The use of hydrogen as a sole fuel in direct injection without an ignition source diesel engine is not practical nor feasible at present. By modifying a production engine to operate as a low-heat-rejection engine, and coupling that with a carefully chosen set of operating parameters, a maximum compression temperature of 800 K was produced. The corresponding combustion chamber surface temperature was estimated to have reached 600-700 K. Lubricant combustion and formation of hot spots were eliminated. Only sporadic compression ignition of hydrogen was achieved. Ignition delay cannot be controlled and varied significantly under identical experimental conditions.

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