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EFFECT OF EGR ON HCCI ENGINE WITH HYDROGEN AS FUEL

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Abstract: *In recent years a great deal of work has been done and the research area has extended to all aspect of the combustion process. It has been gradually presenting a picture of energy saving and cleaner exhaust emissions. Increasing environmental concerns regarding the use of fossil fuels and global warming have prompted researchers to investigate alternative fuels. All engine manufacturers of today are seriously challenged, not only by legislative demands of low emissions, but also by the need to decrease the dependency on non-renewable fuels, such as oil. Hydrogen (H2) has been suggested as a possible replacement for the fuels used today ,the way to reach this goal is to using new combustion concepts, such as Homogeneous Charge Compression Ignition Homogeneous Charge Compression Ignition (HCCI) engines promise high thermal efficiency combined with low levels of nitric oxide and particulate matter emissions where HCCI engines can operate on gasoline, diesel fuel, and most alternative fuels and studies suggest that the concept of an HCCI engine running on H2 would result in a locally emission free engine. The scope of this proposal is to study the key processes involved with* H_2 *HCCI combustion and examine whether the mechanisms of these processes can be easily incorporated into current engines further more to investigate broaden the stable operations range for HCCI a series of experiments were analyzed using hydrogen fuel adaptation and their composition and the exhaust mechanism of the exhaust gas.*

Keywords: HCCI, combustion, fuel efficiency, pollutant emission, alternate fuels, Hydrogen fuel, EGR

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INTRODUCTION

Compression ignition engine are preferred prime movers due to excellent drivability and higher thermal efficiency. Despite their advantages they produce higher levels of NOx and smoke emissions which will more harmful to human health. Hence stringent emission norms have been imposed. In order to meet the emission norms and also the fast depletion of petroleum oil reserves lead to the research for alternative for diesel engines.

Diesel engines currently offer significant fuel consumption benefits relative to other power plants for on and off road applications; however, costs and efficiency may become problems as the emissions standards become even more stringent. Homogeneous charge compression ignition (HCCI) combustion offers a solution to this problem as it achieves gasoline-like emissions while keeping diesel-like fuel-efficiency by operating at lower combustion chamber temperatures. Furthermore, HCCI combustion works with gasoline, diesel and most alternative fuels, giving it a major advantage for future developments.

The concept of homogeneous charge compression ignition (HCCI) has been described before by a number of researchers. Onishi, et al. (1979) experimentally studied homogeneous charge compression ignition in a two-stroke engine and achieved low cyclic variation at idle and up to 40% load. as reported in [22]. Investigators worldwide are developing HCCI engines as this technology has not matured sufficiently. They can be used in either SI or CI engine configurations with a high compression ratio (CR). HCCI engines work without the help of diesel injectors or spark plugs and can achieve high engine efficiency with low emission levels. General Motors Corporation (GM) has unveiled a prototype car with a gasoline HCCI engine and it was claimed that it could cut fuel consumption by 15% [23]. The engine is able to virtually eliminate NOx emissions and lowers throttling losses which assists better fuel economy [24].

In HCCI engines, the fuel and air are premixed to form a homogeneous mixture before the compression stroke. As a result, the mixture ignites throughout the bulk without discernable flame propagation due to occurrence of auto ignition at various locations in the combustion chamber (multi-point ignition). This may cause extremely high rates of heat release, and consequently, high rates of pressurization [3-5]. In HCCI engines, auto-ignition and combustion rate are mainly controlled by the fuel chemical kinetics, which is extremely sensitive to the charge composition and to the pressure and temperature evolution during the compression stroke, therefore HCCI combustion is widely assumed to be kinetically controlled [3, 6, 7]. The main objective of HCCI combustion is to reduce soot and NO_X emissions while maintaining high fuel efficiency at part load conditions [2, 8]. In some regards, HCCI combustion combines the advantages of both spark ignition (SI) engines and compression ignition (CI) engines [8, 9]. The results from experiment and simulation show that the HCCI combustion has a low temperature heat release and a high temperature heat release, and both heat releases occur within certain temperature ranges. The low temperature heat release is one of the most important phenomena for HCCI engine operation and the occurrence of it depends chemically on the fuel type [10-12].

However there are certain number of obstacles and problems in its application that have not been resolved. These problems are the control of ignition and combustion, difficulty in operation at higher loads, higher rate of heat release, higher CO and HC emissions particularly at light loads, difficulty with cold start, increased NO_X emissions at high loads and formation of a completely homogeneous mixture [13-15]. The lack of a well-defined ignition timing control has led a range of control strategies to be explored. Numerous studies have been conducted to investigate HCCI combustion control methods such as intake air preheating [14, 16, 17], Variable Valve Actuation (VVA) [4], Variable Valve Timing (VVT) [1], Variable Compression Ratio (VCR) [18] and EGR rate [10]. Moreover many studies also focused on the effects of different fuel physical and chemical properties to gain control of HCCI combustion [9, 19- 21].

Fuel flexibility in HCCI can be applied for a wide range with different octane/cetane numbers. The combustion process of a HCCI engine has little sensitivity to fuel characteristics such as lubricity and laminar flame speed. Fuels with any Octane or Cetane number can be burned, although the operating conditions must be adjusted to accommodate different fuels, which can impact efficiency. An HCCI engine with variable compression ratio or variable valve timing could, in principle, operate on any hydrocarbon or alcohol liquid fuel, as long as the fuel is vaporized and mixed with air before ignition. Besides gasoline[25] and diesel fuel [26], a variety of alternative fuels, such as methanol [27], ethanol [28,29], natural gas [30], biogas [31], hydrogen [32], DME [27] and their mixtures [33-35], including also gasoline and diesel mixtures and different mixtures of isooctane with heptane [36], have been experimentally proved as possible fuels for HCCI combustion in both two-stroke and four-stroke engines.

The purpose of the present study is to examine the effect of various operating variables of a homogeneous charge compression ignition (HCCI) engine fueled with hydrogen.

HYDROGEN AS A FUEL

Since the HCCI engine depends on the cylinder charge auto igniting, the use of high compression ratios is required. With no charge heating, this was found to be between 18:1 and 25:1 when carrying out simulation studies for the engine. Conventional spark ignition engines are typically limited to a compression ratio of approximately 10:1. The combination of fast heat release in HCCI mode and the use of a lean cylinder charge, gives close to constant volume combustion with low peak gas temperatures leading to reduced heat transfer losses through the cylinder walls and high indicated thermal efficiencies.

Hydrogen possesses some features that make it attractive for use as a fuel in internal combustion engines, enabling fast, close to constant volume combustion, high combustion efficiency and low emissions. Numerous authors have investigated the use of hydrogen in spark ignition (SI) engines, and the feasibility of hydrogen as a fuel in [37]such engines is well established. An overview of the characteristics of hydrogen as a fuel for SI engines was presented by Karim [38].

The flame speed of hydrogen is higher and hydrogen allows operation at significantly higher excess air ratios than conventional hydrocarbon fuels. This enables extended lean burn operation of the engine, potentially leading to a drastic reduction of NO*x* emissions. High diffusivity and low quenching distance avoids poor vaporization problems. Emissions of carbon monoxide and un burnt hydrocarbons are practically eliminated with a hydrogen fuelled engine, as the only source of carbon will be the lubricating oil. For the same reason the engine does not emit carbon dioxide. The only non-trivial exhaust gas emissions will be nitrogen oxides, which result from the oxidation of atmospheric nitrogen under high temperatures. It will be shown below that with HCCI operation and a very lean mixture this pollutant can be reduced to near-zero levels. The ignition energy for hydrogen is low, however the temperature required for auto ignition is significantly higher than that of conventional hydrocarbon fuels. Therefore, CI engines using hydrogen fuel require high compression ratios and/or pre-heating of the inlet air to ensure auto ignition.

The engine used on this research work was a four-stroke, single cylinder, direct injection, naturally aspirated, air-cooled CI engine. The engine was coupled to a hydraulic pump system so that the engine could be operated at varying load conditions. The engine was fitted with an injection system allowing hydrogen to be mixed with the inlet air. Using this setup, the performance of the engine operating in hydrogen fuelled HCCI mode and normal diesel fuelled mode investigated and compared. With the engine running at 2200 rpm, air inlet temperature set at 93°C and a hydrogen flow rate of 90dm^3/min, HCCI mode of operation was tested.

With the objective of determining the leanest cylinder charge that the hydrogen fuelled HCCI engine can operate smoothly, a series of test were carried out with varying fuel-air ratio. Figure 1 illustrates the brake thermal efficiency as a function of the excess air ratio, λ. It can be seen that the engine is able to operate with extremely lean cylinder charges and still maintain a relatively high thermal efficiency when compared to conventional diesel engine operation. Figure 2 shows the in-cylinder gas pressure for 10 consecutive engine cycles with the engine running at 2200 rpm with an air excess ratio of 3. The engine brake thermal efficiency under these conditions was found to be approximately 45%. This is a significant increase in the thermal efficiency compared to its value under conventional operation using diesel fuel.

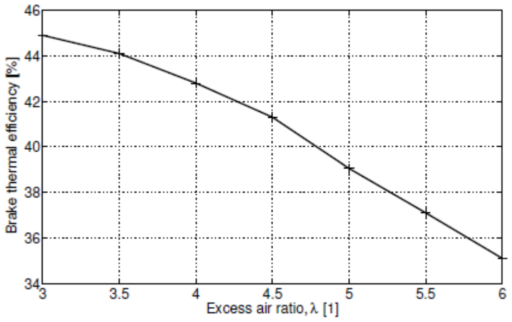

Figure 1: Engine brake thermal efficiency.

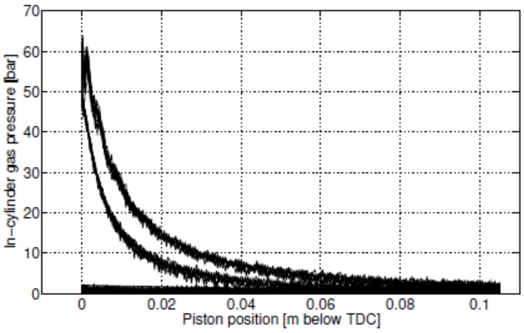

Figure2:Cylinder pressure plots in HCCI

The ignition angle (α_{ign}), governs the combustion process, and control of the ignition timing is of high importance in order to optimize engine operation. Figure 3 shows how the ignition timing is nearly linearly dependent on the inlet air temperature for the HCCI operational mode. This indicates that control of the inlet air temperature can be used to control ignition timing for the hydrogen fuelled HCCI engine. Figure 4 indicates that an increase in the air inlet temperature results in a decrease of engine power output. The brake thermal efficiency and the indicated mean effective pressure decrease with an increase in the air inlet temperature.

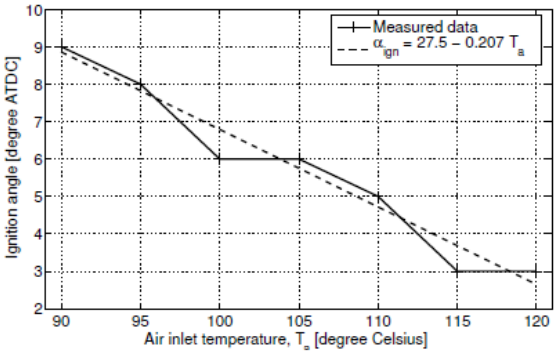

Figure 3: Ignition angle for Varying engine power out put.

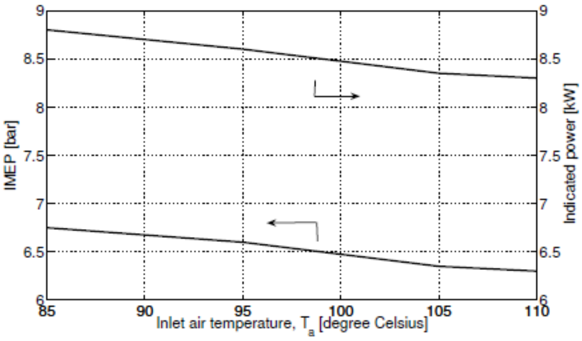

Figure 4: Effect of inlet air temperature on inlet air temperature

The exhaust emissions were measured while the engine was operated in hydrogen fuelled HCCI mode at a speed of 2200 rpm and *Ta* of 100◦C. The results of the test are presented in Figure 5 As can be seen, the NO*x* emissions increase sharply for λ > 3.5, due to the increasing in-cylinder gas temperatures, and become negligible for higher values of λ. The NO*x* levels are considerably lower that what would be expected for conventional diesel engine operation for all the cases investigated.

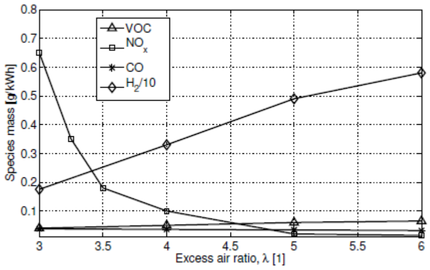

Figure 5: H_2 HCCI engine exhaust gas emissions levels.

The Experimental results[39] that presents that, the peak in-cylinder pressures and the rates of pressure rise were higher in the HCCI hydrogen engine than for conventional operation on diesel fuel, limiting the HCCI engine to part load operation and potentially requiring design changes to maintain engine reliability. The fuel efficiency obtained was, however, significantly higher than that obtained when operating as a conventional diesel fuelled engine, and high efficiency was obtained even with very lean cylinder charges. The inlet air had to be heated in order to ensure auto ignition and it was demonstrated that the inlet air temperature is the most useful variable to control ignition timing. Engine emissions were measured shown that negligible levels of all exhaust emissions were produced, including nitrogen oxides, compared to conventional diesel-fuelled operation.

Better understanding of the HCCI combustion process can be greatly aided by exploration of the chemical processes occurring in the combustion process, such as the effect of fuel structure on combustion timing. It is possible to observe combustion characteristics of the fuel-in-air charge by collecting exhaust samples at different combustion timing.

Combustion timing is determined by a number of different parameters, such as equivalence ratio, intake manifold pressure, and intake manifold temperature. The primary influence on combustion timing is the intake manifold temperature of the fuel-in-air mixture inducted into the engine combustion chamber.

The devices such as electrical heaters, heat exchangers, and exhaust gas recirculation (EGR) control the intake manifold temperature(T_{in}).The composition of the fuel also plays a major part in the ignition process, as different fuels possess different auto ignition characteristics.

Hountalaous et al using 3D-multi dimensional model to examine the effect of EGR temperature on a turbocharged DI diesel engine with three different engine speeds, and they reported that high EGR temperature affects the engine brake thermal efficiency, peak combustion pressure, air fuel ratio and also soot emissions, and the combined effect of increased temperature and decreased O2 concentration resulted low NOx emissions. Also they suggested that EGR cooling is necessary to retain the low NOx emissions and prevent rising of soot emissions without affecting the engine efficiency at high EGR rates. Ken Satoh et al [4] investigated on a naturally aspirated single cylinder DI diesel engine with various combinations of EGR, fuel injection pressures, injection timing and intake gas temperatures affect exhaust emissions and they found that NOx reduction ratio has a strong correlation with oxygen concentration regardless of injection pressure or timing. NOx reduction ratio is in direct proportion to intake gas temperatures. EGR may adversely affect the smoke emission because it lowers the average combustion temperatures and reduces the oxygen intake gases, which in turn keeps soot from oxidizing.

EFFECT OF EGR IN HCCI ENGINE

According to different methods of the exhaust gas recirculation, EGR technique can be divided into internal EGR and external EGR. The internal EGR rate can be obtained by changing valve overlap period to negative valve overlap (NVO) and the external EGR rate can be adjusted by using an EGR valve. For high-octane fuel (such as: gasoline) HCCI, negative valve overlap (NVO) is recognized as one of the possible implementation strategies of HCCI closet to production. The effect of inlet air temperature through NVO is insignificant when the engine runs well inside of the HCCI operating range [40, 42]. The effect of EGR on HCCI combustion can be divided into three parts: a dilution effect (inert gasses present in the EGR), a thermal effect (heat exchange, thermal loss to the wall, EGR ratio mixture quality, EGR temperature, heat capacity), and a chemical effect. The chemical effect influences not only the overall kinetics, but it also can change a specific reaction path, which makes this effect particularly interesting for the investigation of the auto ignition process [43]. The effects of EGR that have been investigated are: increase in intake charge temperature (heating effect), reduction of oxygen concentration (dilution effect), increase in specific heat of the mixture (heat-capacity effect), chemical interactions involving the CO_2 and H_2O species of the recycled burned gases (chemical effect), and stratification of the recycled burned gases (stratification effect) [41,44]. The dilution and heat capacity effects are responsible for reducing the heat-release rates and delaying HCCI combustion. The heating effect is mainly responsible for the advance timing of auto-ignition, and the residuals stratification effect facilitates HCCI combustion. Reactive species, present in the residuals, facilitate auto-ignition, and the inert species slow down the combustion rate (dilution effects) [41, 43, 44]. EGR provides the appropriate temperature to enhance auto-ignition, while maintaining the combustion temperature sufficiently low.

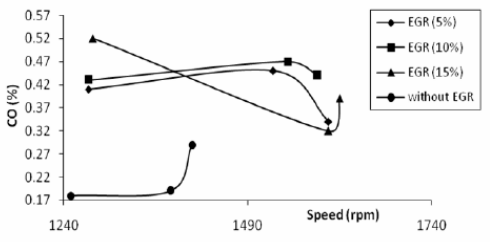

Figure 6: Effect of engine speed variations on CO emission of emission of dual fuel HCCI-DI

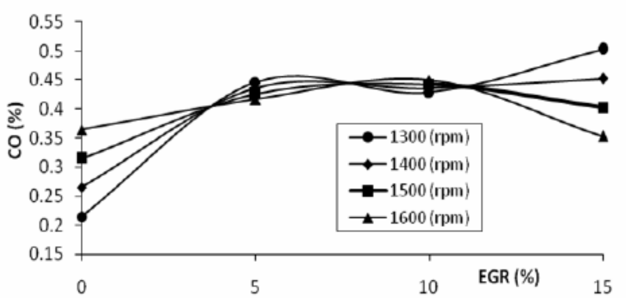

Figure7: Effect of EGR on CO on dual fuel HCCI-DI engine at different Engine speeds

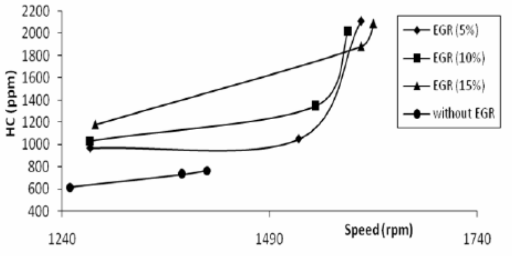

Figure8: Effect of engine speed variations on HC emissions of dual fuel HCCI-DI engine

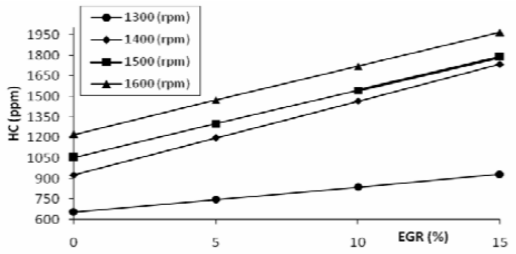

Figure9: Effect of EGR on HC emissions of dual fuel HCCI-DI engine at different engine speeds

The research was done to study the effects of EGR rate and engine speed variation on CO and HC emissions of gasoline-diesel dual fuel, Hydrogen fuelled HCCI engine & [45,46]. Results can be summarized as:

1) An advantage of dual fuel engine, which was noticed in all tests, was fast and easy transition to HCCI mode.

2) Increasing EGR dilutes the intake charge and reduces the amount of oxygen. Dilution also decreases combustion temperature and leads to incomplete HCCI combustion and therefore increases CO emission.

3) The insufficient time for formation of homogeneous charge mixture, caused by increasing engine speed, results in increase of CO emissions.

4) High engine speeds in HCCI mode results in insufficient time for formation of homogeneous mixture cause more HC emission due to incomplete HCCI combustion.

5) Increasing EGR rate dilutes the intake charge and reduces its oxygen. Dilution also decreases combustion temperature, which results in reduction of the amount of burnt fuel thus HC emission increases in comparison with no EGR.

6) HCCI can be induced and controlled by varying the mixture temperature, either by Exhaust Gas Recirculation (EGR) or intake air pre-heating.

7) A combination of HCCI combustion with hydrogen fuelling has great potential for virtually zero CO_2 and NO_X emissions. Nevertheless, combustion on such a fast burning fuel with wide flammability limits and high octane number implies many disadvantages, such as control of backfiring and speed of auto ignition and there is almost no literature on the subject, particularly in optical engines.

8) Experiments were conducted [46] in a single-cylinder research engine equipped with both Port Fuel Injection (PFI) and Direct Injection (DI) systems running at 1000 RPM. Optical access to in-cylinder phenomena was enabled through an extended piston and optical crown. Combustion images were acquired by a high-speed camera at 1° or 2° crank angle resolution for a series of engine cycles.

9) Spark-ignition tests were initially carried out to benchmark the operation of the engine with hydrogen against gasoline. DI of hydrogen after intake valve closure was found to be preferable in order to overcome problems related to backfiring and air displacement from hydrogen’s low density.

10) HCCI combustion of hydrogen was initially enabled by means of a pilot port injection of n-heptane preceding the main direct injection of hydrogen, along with intake air preheating.

CONCLUSION

From the study it was observed that the peak in-cylinder pressures and the rates of pressure rise were higher in the HCCI hydrogen engine than for conventional operation on diesel fuel, limiting the HCCI engine to part load operation and potentially requiring design changes to maintain engine reliability.

As a consequence of the higher rates of pressure rise and peak pressures, additional design considerations must be given to the piston pin, crank bearings and piston rings, since their load carrying capacity should be taken into account if the reliability of the engine is to be maintained.

Sole hydrogen fuelling HCCI was finally achieved and made sustainable, even at the low compression ratio of the optical engine by means of closed-valve DI, in synergy with air-pre-heating and negative valve overlap to promote internal EGR. Various operating conditions were analyzed, such as fuelling in the range of air excess ratio 1.2–3.0 and intake air temperatures of 200–400 °C. Finally, both single and double injections per cycle were compared to identify their effects on combustion development.

Further the study analyzed that compression ratios beyond 12 are likely to produce severe knock problems for the richer mixtures used at high load conditions. It seems that the best compromise is to select the highest possible CR to obtain satisfactory full load performance. The choice of optimum compression ratio is not clear; and it may have to be tailored to the fuel and other techniques used for HCCI control. So , a variety of physical control methods (e.g., EGR) have been examined in an effort to obtain wider stable operation. From these investigations and many others in the past few years it appears that the key to implementing HCCI is to control the charge auto ignition behavior which is driven by the combustion chemistry.

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