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Effect of Water Injection on NO_x Emission and Combustion of a Hydrogen-Fueled SI Engine

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Abstract: This paper experimentally investigates the effect of manifold injection of water on performance and NO_x emissions in a hydrogen-fueled spark ignition (SI) engine. One of the important difficulties with hydrogen-fueled internal combustion engines is the high NO_x level due to rapid combustion. In this study, tests were carried out on a single cylinder SI engine equipped with electronically controlled hydrogen and water injection systems. The engine was run at different load conditions at full throttle and at a constant speed of 3000 rpm. NO_x levels were found to rise after a brake power 0.72 kW, maximum value was about 5890 ppm without water injection. Severe drop in NO_x levels to even as low as 1930 ppm was found with 2.5 kg/h water injection rate at MBT and further 38.7 % reduction of NO_x can be achieved by retardation of spark timing from MBT. However, it is not possible without sacrificing little thermal efficiency due to retardation of spark timing. The experimental data showed that high reductions in NO_x emission confirm the great effectiveness of water injection in reducing the engine environmental impact. Final results have shown that water injection really proved a great technique to avoid detonation and to control NO_x formation in a hydrogen-fueled SI engines.

Key words: Hydrogen · Water addition · Spark-ignited Engine · Combustion pressure · Manifold Injection · Emission

INTRODUCTION

With the increasing concern about scarcity of cured oil supply and environmental protection, research on improving engine performance and reducing the exhaust emission has made the authors to focus on the utilization of alternative fuels in SI engine. The growth of alternative fuel engines has attracted more of the engine community because the consumption of fossil fuels has almost increased in the past three decades [1]. Alternative fuels usually belong to clean fuels compared to gasoline in the combustion process of engine. These alternative fuels are valuable to slow down the fuel shortage and reduce harmful engine exhaust emissions. Although hydrogen is accepted as the clean fuel, it is more suitable for spark ignition engines with minor modifications [2-7]. Hydrogen is an excellent fuel for SI engine due to its unique characteristics like much better lean burn capability, high speed flame propagation, very small quenching distance and so on [8].

There are some drawbacks reported with hydrogen usage in engines. They are high NO_x, backfire, knocking etc. NO_x emission still remains a high value under high load conditions. The peak cycle temperature goes up when the load is increased, which tends to accelerate NO_x formation. The fuel-air mixture in the inlet manifold to get ignited by hotspots due to the lower ignition energy of hydrogen fuel and creates backfire. The timed manifold injection of hydrogen has been found to be a good technique to avoid back-firing.

Several techniques have been tried to suppress NO_x formation. Some of them are use of catalytic converter, use of exhaust gas recirculation, turbo-charging with intercooling, addition of diluents or water injection with the intake charge, etc [9-13]. The water injection along with fuel-air mixture has been considered repeatedly since the early development of internal combustion engines. Water has been added as an internal coolant, as a knock suppressant and a means to control emission [14]. Water injection in the form of fine spray into the intake

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manifold has been found to be an effective and low-cost method to reduce NO_x emission in SI and compression ignition engines. The mass ratio of water and hydrogen of 4:1 was reported as an optimum value for reducing NO_x emissions. Nearly 60% reduction in NO_x has been reported with water injection in a gasoline-fueled engine [15]. The reduction of NO_x is also strongly dependent on water injection timing. When water is injected between the range of -60 to -20°CA ATDC, with more than 50% NO_x being removed. The water injection timing of -40°CA ATDC is optimum injection timing. At this water injection timing, nearly 60.8% of NO_x emissions reduction has been reported [16]. Increasing the humidity of intake charge was also reported as an efficient method to reduce the NO_x with the intake charge at different proportions on study of performance, emission and combustion parameters have been reported. The use of water-fuel emulsion for controlling NO_x emission was also reported by many authors. The 10% water in gasoline by volume caused 20% reductions in oxides of nitrogen and also found that an instability of emulsified fuel was the main drawback encountered in the utilization of water-fuel emulsions [17-18].

Extremely fast burning of hydrogen tends to occur at a very high rate of pressure rise, which leads to engine knocking [19]. The hydrogen knocking creates enormously high mechanical stresses and temperatures, which are also responsible for the rise of NO_x emissions. The compression ratio, temperature of inlet charge and spark timing have a prominent effect on knocking in hydrogen fueled engine [20]. Along with hydrogen adding argon gas is also a method for suppressing knocking. Supplying more amount of hydrogen and running the engine at mixture richer which reduces the tendency of knocking. However, the unburnt hydrogen can be taken from the exhaust and can be recycled [21]. The effect of spark timing on combustion of hydrogen was studied and it was found that spark timing has a noticeable effect on the degree of constant volume combustion and thus affects thermal efficiency [22]. The reduction of nitric oxide emissions can be done by retarding the spark timing with slight sacrifice in thermal efficiency of an in-cylinder injected hydrogen engine [23-24].

The concept of water addition along with fuel-air mixture of hydrogen engine can be essentially characterized as low NO_x emission, reduction of back fire and good combustion stability. The objective of this paper is to clarify the effect of water injection on NO_x emission and combustion parameters of SI engine. Water was supplied by an electronic injection system inclusive of a comparatively high pressure electronic pump. The water injector was located in the intake manifold shortly before the inlet valve. The experimental test data of hydrogen engine with baseline test without water injection and with various quantities of water injections say 0.5, 1.0, 1.5, 2.0 and 2.5 kg/h were compared to identify the effect of water injection on performance, combustion and NO_x emissions.

Present Study: In the present work, a gasoline-fuelled SI engine has been modified to operate with neat hydrogen along with water injection. The operating parameters of the engine have been varied to determine their influence on performance, emission and combustion characteristics. An electronically controlled manifold injection approach has been used to control and supply the hydrogen and water. The electronic spark timing system was also implemented to vary the spark timing and maintain best spark timing.

Experiments have been conducted at five different load conditions from 0.1 to 1.88kW. For every load, finely atomized water was injected at different rates in the range of 0 to 2.5 kg/h in steps of 0.5 kg/h and the engine was run at the best ignition timing. Emission of NO_x and other combustion parameters with various water injection rates was recorded. Subsequently, the effect of water injection rate on suppressing knock and NO_x emission has been studied. Also, performance parameters like brake-specific fuel consumption, brake thermal efficiency, exhaust gas temperature, emissions of HC, CO and NO_x and combustion parameters like peak pressure and heat release rate, were studied and compared.

Experimental Setup: The experiments were carried out on a four-stroke, single cylinder, overhead valve, spark ignition Greeves cotton engine. An eddy current dynamometer was directly coupled to the engine used for applying load. Table 1 shows the specifications of the engine. Since the original engine was designed to be used as a gasoline engine, several modifications were made in order to adapt hydrogen and water injection in the manifold of the engine.

Fig. 1 shows a schematic view of the experimental setup. A special hydrogen gas fuel injector made by Quantum fuels and an electronic water injector were mounted on the inlet manifold to supply hydrogen and water simultaneously to the engine. Both the injectors were controlled separately by using a self-developed electronic control unit (ECU).

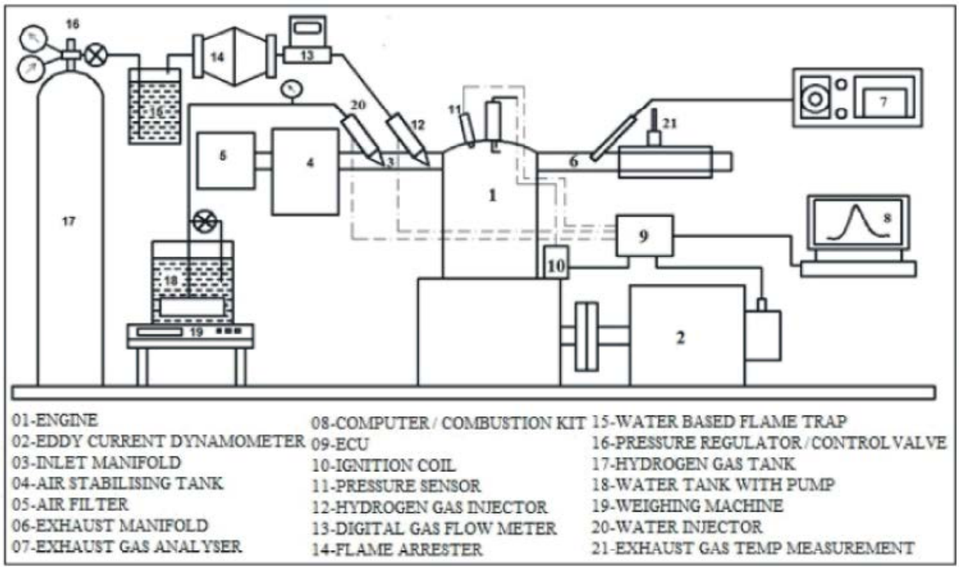

Fig. 1: Schematic view of the Experimental setup

Fig. 2: Photographic view of Experimental setup

Table 1: Specification of Test Engine

Items	Values
Engine	Greaves Cotton
Type	4-Stroke
Power	2.2kW
Speed	3000rpm
Bore	70mm
Stroke	67.7mm
Displacement	256 CC
Compression Ratio	4.67 : 1

The injection timing and duration can be adjusted by using ECU. In addition to it, ignition control unit (ICU) was also developed and incorporated for maintaining minimum spark advance for best torque (MBT). Fig. 2 shows photographic view of experimental setup.

Gaseous hydrogen with a purity of 99.995% stored in a cylinder was fed to the engine through various safety devices. Table 2 shows the properties of hydrogen. A regulator was used to bring down the pressure of hydrogen from 140 to 2 bar. To prevent backfiring travel to the cylinder, the gas coming out of the cylinder was allowed to pass through a water flame trap along with a flashback type arrester in the series. Fig. 3 shows the photographic view of hydrogen flow line. A portable hydrogen leak detector was also used during experiments to find any leakage in the hydrogen flow line and joints. The combustion pressure data were acquired using a spark plug-type piezoelectric pressure sensor and crankshaft position was measured by an encoder (Kistler's) with the resolution of 1 degree crank angle.

Fig. 3: Photographic view of Hydrogen flow line

Table 2: Properties of Hydrogen

Property	Hydrogen
Limits of flammability in air, vol. %	4-75
Minimum energy for ignition, mJ	0.02
Quenching gap in NTP air, cm	0.064
Auto ignition temperature, K	858
Stoichiometric air fuel ratio	34.4
Flame speed at 2C, cm/s	237
Diffusion coefficient in NTP air, cm2/s	0.61
Heat of combustion (LCV), MJ/kg	119.93

The signals from the encoder and pressure sensor were analyzed by a combustion analyzer to understand in-cylinder combustion phenomena. All of the sensing data were acquired by a data acquisition system.

Experimental Procedure: The test was carried out at an engine speed of 3000 rpm with wide open throttle (WOT). The experiment was started after the engine has warmed up. The engine brake power was varied by varying the hydrogen flow rate by increasing the injection duration and load applied. The load range is varied from 0 to 1.88kW and the manifold water injection rate was varied from 0 to 2.5 kg/h. At each operating condition, the spark timing was set at minimum spark timing for best torque (MBT). The flow rate of water was measured by using a weighing machine with 0.5 g accuracy by with time taken for known grams of water injected and the hydrogen flow can be measured by using digital Alicat gas flow meter of 0.2% accuracy at full scale. Dry exhaust gas trapped from the exhaust manifold was used to measure exhaust emissions. The exhaust gas constituents (CO, CO_2, HC, O_2 and NO_x) were measured by a five gas analyzer (Model Horiba MEXA- 534L). Before each test run, the analyzer was calibrated using calibration gas of known concentrations and the calibration rechecked at the end of each experiment to confirm not to undergo deviations during testing. Performance, emission and combustion characteristics were then estimated and analyzed. Later, experiments were carried out on the above engine with water injection into the intake manifold at different flow rates to study its influence on NO emissions and combustion parameters.

RESULT AND DISCUSSION

The performance, emission and combustion characteristics of neat hydrogen-fuelled SI engine with varying water injection are presented and discussed in the following sections.

Brake-Specific Fuel Consumption: Fig. 4 shows the variation of brake-specific fuel consumption. The brake-specific fuel consumption is higher for higher water injection rate. This is because the injection of water cools the hydrogen-air mixture significantly, which increases its density and hence the amount of mixture that enters the cylinder is also increased. The water may absorb heat as the charge is compressed, thus reducing compression work and therefore it reduces knock.

Brake Thermal Efficiency: Fig. 5 shows the variation of brake thermal efficiency with brake power. The brake thermal efficiency was decreased with the increase in the rate of water injection rate for the same input of hydrogen fuel. The maximum brake thermal efficiency was 31.39% at 1.44 kW brake power for neat hydrogen but there is a less than 2% reduction was observed for 2.5 kg/h water addition at the same load. Water addition allows more gaseous fuels to escape the combustion process as

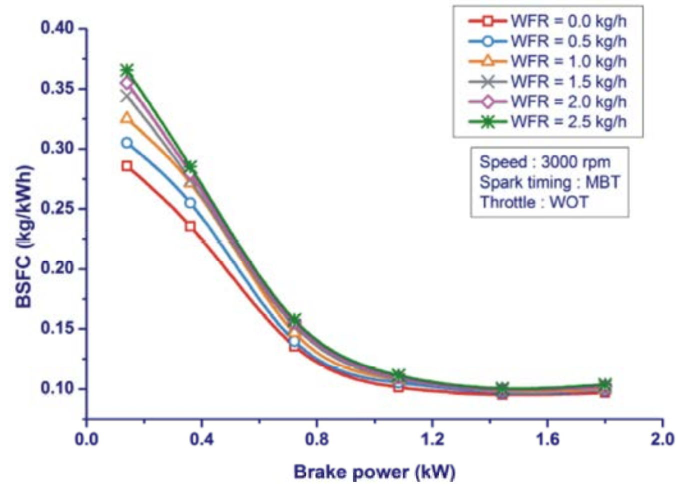

Fig. 4: Variations of brake-specific fuel consumption with brake power

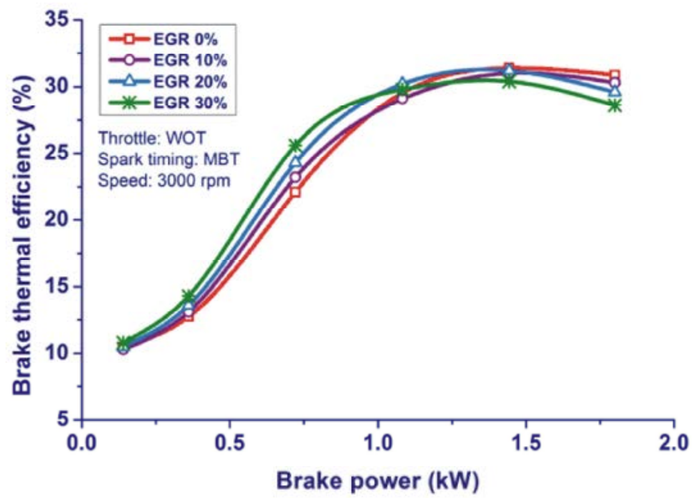

Fig. 5: Variations of brake thermal efficiency with brake power

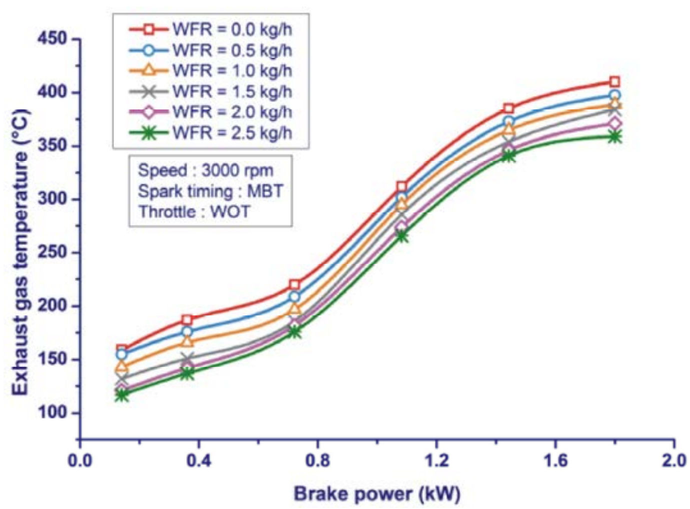

Fig. 6: Variations of exhaust gas temperature with brake power

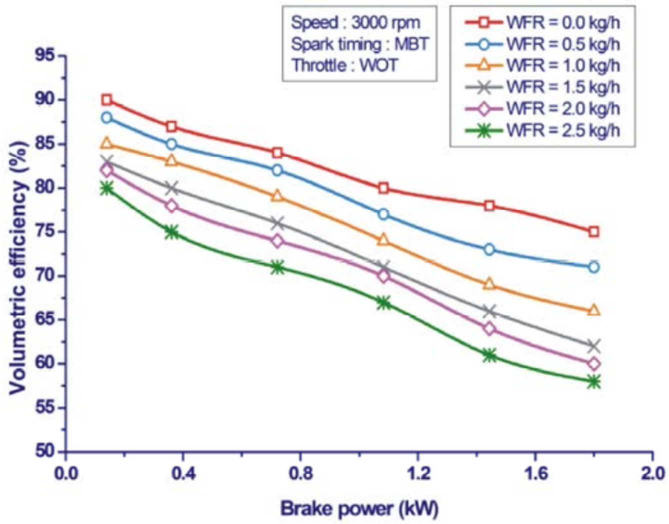

Fig. 7: Variations of volumetric efficiency with brake power

a result of the quenching due to the reduction in the cycle temperature. Hence, the brake thermal efficiency drops little with the increase in water injection. However, with the addition of water, the brake thermal efficiency in the range beyond the knock limited power output of the hydrogen engine.

Exhaust Gas Temperature: The variation in the exhaust gas temperature is shown in Fig. 6. The exhaust gas temperature reduces with an increase in the rate of water injection through the inlet manifold. This is due to the reduction in cycle temperature. About 51°C drop in temperature was found in the exhaust gas with maximum water injection rate at peak load.

Volumetric Efficiency: The Fig. 7 shows the graph between brake power versus volumetric efficiency. The volumetric efficiency is based on quantity of air intake. From the graph, it is observed that the volumetric efficiency decreases as the brake power is increased. This is mainly due to the fact that as the amount of hydrogen supply increases, it displaces the equal amount of air intake from the engine cylinder. At higher loads, the engine temperature is quite high which increases the water vaporization causing a noticeable drop in volumetric efficiency. It is found that only around 25.6% drop in volumetric efficiency was observed for the maximum water injection rate 2.5 kg/h when compared with neat hydrogen without water injection.

Cylinder Pressure: Fig. 8 shows the pressure crank angle diagram hydrogen engine with various water injection rates. It is observed that due to rapid combustion of hydrogen, the cylinder peak pressure values are found to be higher. It is also found that there is a significant drop in peak pressure for various water injection rates due to the inlet charge dilution by water injection. The higher value of peak pressure in the hydrogen fueled engine is attributed to faster burning rate of hydrogen.

Heat Release Rate: Fig. 9 shows the variation of heat release rate with crank angle. From the graph, it is clearly found that there is a significant decrease in heat release rate for various water injection rates. The start of the combustion is delayed with the increase in the quantity of water in the inlet charges. It is observed that till the water injection rate of 1 kg/h, the reduction in the heat release is found to be around 12%. But further increase in the water injection rate to 2.5kg/h has reduced the heat release rate by 23%. This clearly indicates that there is an increase in the combustion duration and there is a shift in the peak heat release rate toward the TDC.

Oxides of Nitrogen: Fig. 10 shows the relationship of oxides of nitrogen and brake power for various water injection rates. Only the regulatory emission in hydrogen fuelled engine is nitrogen oxide. NO_x emission is higher during higher load conditions. In general, the increase in the amount of the injected water leads to reduction in the NO_x emissions. Even a water flow rate of 0.5 kg/h is sufficient to cause a significant drop in the NO_x emissions. At 2.5 kg/h water flow rate, the NO_x falls from 5890 to 1538 ppm. The maximum NO_x reduction reached 73.88% at a water flow rate of 2.5 kg/h. This indicates that the water injection timing and amount have a significant effect on NO_x formation rates.

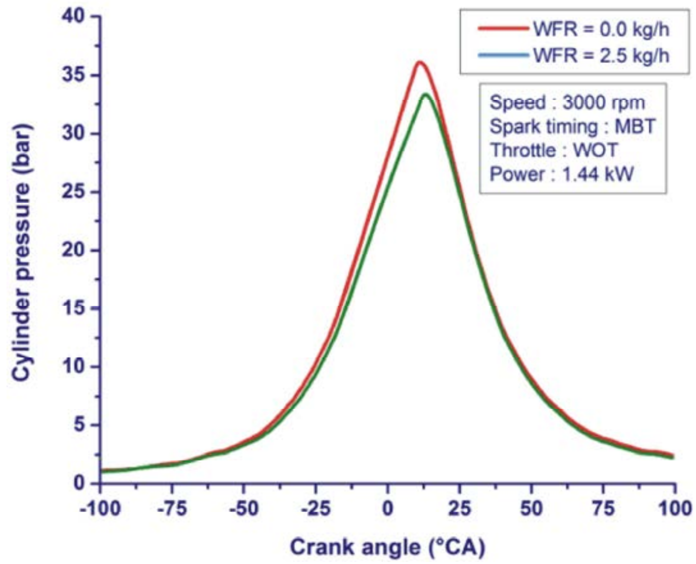

Fig. 8: Variations of cylinder pressure with crank angle

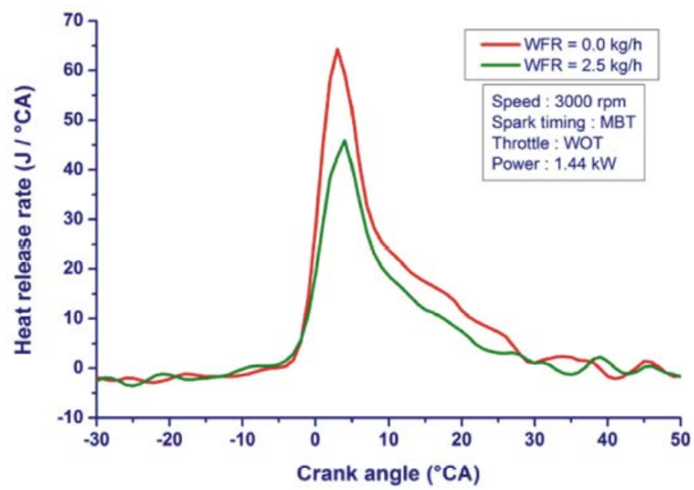

Fig. 9: Variation of heat release rate with crank angle

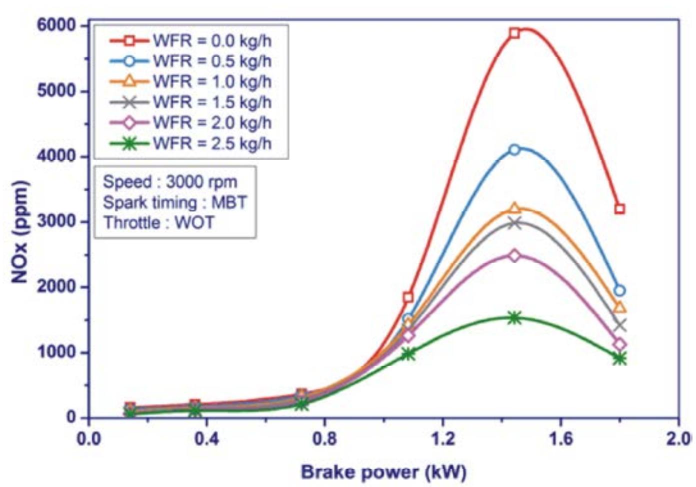

Fig. 10: Variations of oxides of nitrogen with brake power

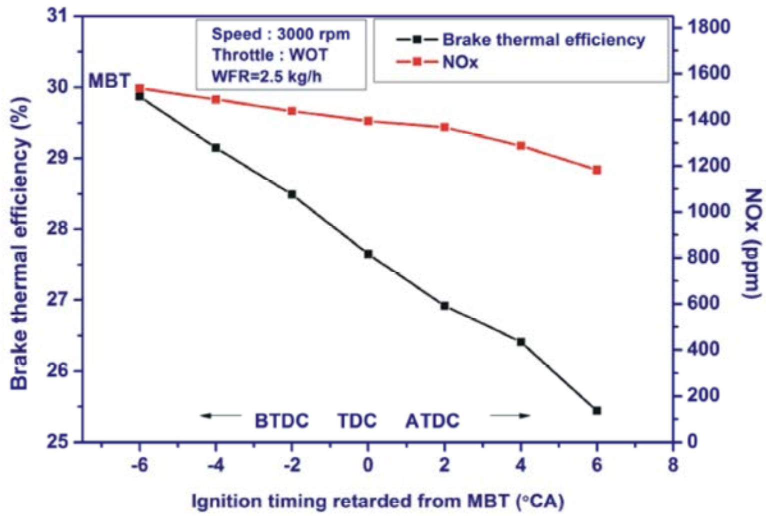

Fig. 11: Effect of ignition timing retardation on brake thermal efficiency and NO*x*

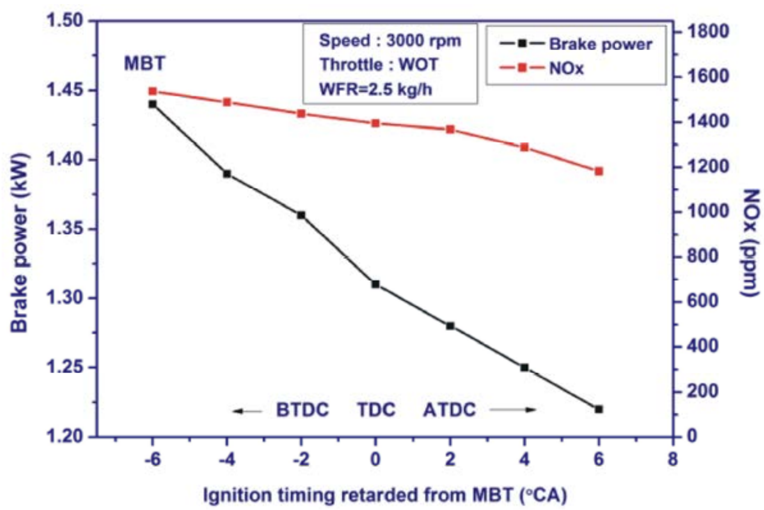

Fig. 12: Effect of ignition timing retardation on brake power and NO*x*

Retardation of Ignition Timing from MBT: Fig. 11 and 12 show the variation of NO_x emission, brake thermal efficiency and brake power with retardation of spark timing from MBT. It is clearly observed that NO_x emission is greatly affected by the spark timing.

No_x emissions decrease as the spark timing is retarded from the MBT. This is because of the reduction in the peak temperature due to the reduction in the cylinder pressure. The lowest NO_x emissions are achieved at an early stage, but there is a drop of 16.3% brake thermal efficiency and 15.2% power output at 1.44 kW with 2.5 kg/h water injection rate. A great reduction in NO_x emission can be achieved only by sacrificing little thermal efficiency and power due to retardation of spark timing MBT.

Carbon Monoxide and Hydrocarbon Emission: Figures 13 and 14 show the variation of carbon monoxide and hydrocarbon emission with brake power. The combustion of lubricating oil in the combustion chamber causes the production of CO and HC emission in a hydrogen fueled engine. In this study, the emissions of CO and HC are very low, CO is less than 1% by vol. CO levels were relatively high at higher loads. Water injection caused a little drop in carbon monoxide emission concentrations at higher water injection rates; this effect was more noticeable at higher load conditions. The 32 % reduction of CO emission was seen at 1.44 kW with 2.5 kg/h water injection rate. Conversely, the same water injection caused about 31% increase in hydrocarbon emissions in the exhaust gas at peak load.

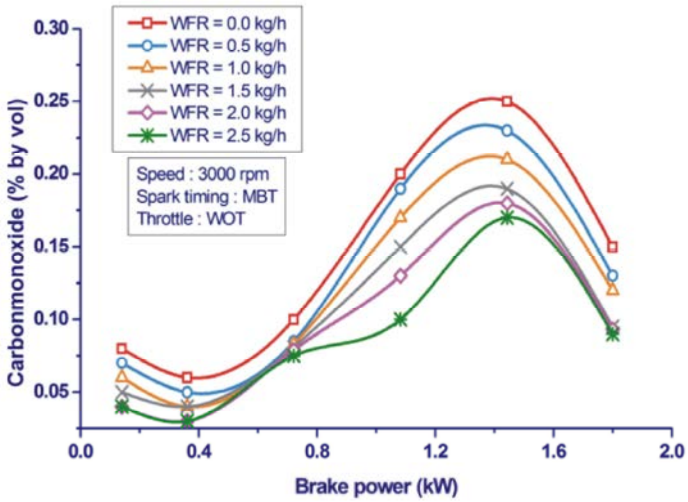

Fig. 13: Variations of carbon monoxide with brake power

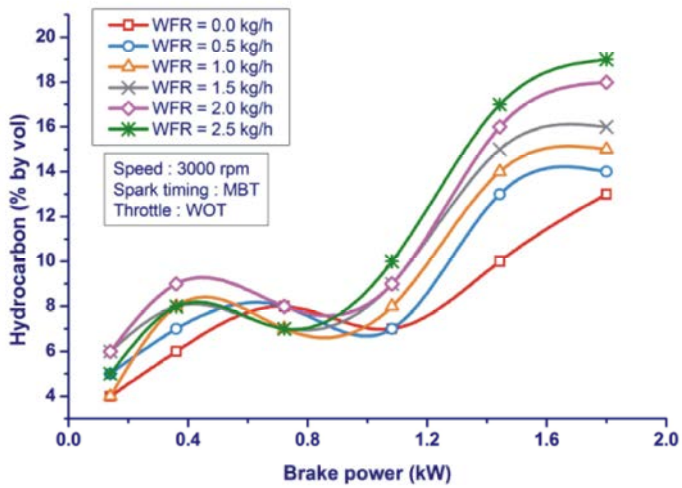

Fig. 14: Variations of hydrocarbon with brake power

CONCLUSIONS

An experiment aiming at investigating the performance, combustion and emission of a hydrogen-fueled engine under various water injection rates at different load conditions was introduced in this paper. The main conclusions are drawn as follows.

- The maximum power produced by the hydrogen engine is 1.83kW which is 82% of the rated power of the original engine.
- Brake thermal efficiency is not much affected by water injection technique. A reduction of less than 5% brake thermal efficiency was seen between 0 kg/h and 2.5 kg/h water injection rate at peak load conditions.
- In hydrogen-fueled engine, manifold injection of water can be an effective and simple method of controlling the nitric oxide emission. The reduction in NO_x emission is strongly dependent on the quantity of water injected in the inlet manifold. The NO_x level was very low at lower load conditions. Experimental measurements proved that NO_x emission reduction of about 73.88% can be achieved by 2.5 kg/h water injecting rate when compared with 0 kg/h water injection rate at 1.44 kW. This is because of the reduction in flame temperature due to inlet charge dilution by water injection.
- Further NO_x emission reduction can also be achieved by spark retardation technique but at the same time brake thermal efficiency is also reduced to 12%. Hence, spark retardation from MBT is not an effective way of controlling NO_x emission. NO_x reduction is not possible without sacrificing little thermal efficiency due to retardation of spark timing from MBT.

- Heat release rate is significantly high for hydrogen-fueled engine due to the high flame temperature and very fast burning of hydrogen.
- A little drop in carbon monoxide emission was seen at higher water injection rate due to quenching layer thickness and gas temperature. However, the hydrocarbon emission is slightly increased by increasing quantity of water injection due to an increased quenching layer thickness.

In general, water injection is a good method of controlling the detonation and reducing the NO_x emissions. However, water injection technique leads to some complications such as jam of moving parts due to corrosion, contamination of lubrication oil, scale formations, damage of electronic water injector, etc.

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