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Experimental Study on the Use of EGR in a Hydrogen-Fueled SI Engine

P. Tamilarasan, M. Loganathan

Abstract— An experimental investigation on the effect of EGR rate on the performance and NO*x* emission of a hydrogen-fueled SI engine was conducted. The hydrogen-fueled engine equipped with manifold-fuel injection was cheaper than fuel cell technologies and also an alternative to conventional fuel engines due to worldwide stringent emission norms. The main objective of this study is to reduce engine exhaust emissions, to decrease the fuel consumption and to run the engine smoothly free from knocking. Hydrogen engines with external mixture formation of hydrogen-air have a significantly lower power output than gasoline engines because of the lower volumetric energy density of the mixture and existence of abnormal combustion phenomena mainly knock. It is well known that the only regulatory emission present in the hydrogen engine is NO*x*. The use of EGR is one of the effective methods for reduction of NO*x* formation in the engine and also it is used to reduce combustion knock. Tests were conducted on a single cylinder engine with a constant speed of 3000 RPM under various load conditions with wide open throttle and optimum spark timing for all test conditions. In this paper, the results of performance and emission were measured for varying values of EGR rate say 0% to 30% over loads. Comparative results of these tests are provided. The test result showed that the brake thermal efficiency for 30% EGR rate is 15.83% higher than 0% EGR at lower loads. However, it is 7.3% lower than the 0% EGR rate at maximum load conditions. The experimental results also showed that the NO*x* concentration decreased with the increase in EGR rate. The peak NO*x* value reached at 1.44 kW for the 0% EGR rate and it was found that 73% reduction of NO*x* can be achieved by 30% EGR rate at the same load. It is also found that a little variation of HC emission at lower loads for all EGR rates and HC shows a significant increase at peak load conditions.CO emission is also negligible.

Index Terms— SI Engine, Hydrogen, Manifold Injection, Exhaust Gas Recirculation, Emission, Backfire, Combustion.

1 Introduction

MOST of the present world's energy demands are still met by the depleted fossil fuels like oil, coal, and natural gas. Many active research interests in non-polluting and renewable fuels for internal combustion (IC) engines are stimulated due to the limited world reserves of primary energy and strict engine emission norms. It is well known that the gas coming out of the combustion of fossil fuel produces sever problems like it degrades the purity of air, creates acid rains, damages ozone, global warming, etc. These problems can be eliminated by replacing the fossil fuel by a number of alternative energy sources, one such is hydrogen [1], [2]. These fuels are a very attractive substance for the role of the energy vector in many practical applications. Hydrogen possesses excellent features that make it an attractive fuel for internal combustion engines, fast burning, high combustion efficiency and low emissions [3], [4], [5]. Many authors have investigated the feasibility of hydrogen and the use of hydrogen fuel for spark ignition (SI) engines which was better than compression ignition engine due to its high self ignition temperature[6], [7]. Some authors have studied the overview of hydrogen-fueled SI engine characteristics [8], [9], [10]. The ignition energy needed for hydrogen is very low; however, the temperature required for self-ignition is significantly higher than that of conventional hydrocarbon fuels such as gasoline and diesel. Thus hydrogen is more suitable for SI engines. The flame speed of hydrogen is higher than conventional hydrocarbon fuels and hydrogen allows operation at significantly higher excess air ratios. This enables extended lean burn operation of the engine, potentially leading to a drastic reduction in oxides of nitrogen 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, but the source of carbon emission in hydrogen engine is due to the burning of lubricating oil in the combustion chamber along with hydrogen-air mixture. For similar reasons, the engine does not produce carbon dioxide emission.

The NO*x* is the only main emission produced in the pure hydrogen IC engine exhaust and it plays more than 95% of all the exhaust emissions generated by the engine. NO*x* is produced due to the result of the oxidation of atmospheric nitrogen under high temperatures in the combustion chamber [11]. There are various techniques available for NO*x* reduction in the engine, and exhaust gas recirculation (EGR) is the most frequently proposed method for NO*x* control [12]. The principle of EGR is to re-inject a fraction of exhaust gas inside the intake manifold, reducing the combustion temperature either by dilution effect or by an inert gas effect with a higher specific heat ratio. The cooled EGR was a more effective method of reducing NO*x* emission when compared with hot EGR [13]. The EGR flow temperature is maintained less than 70°C for all test points to reduce the backfire and knock occurrences and thermal efficiency of cooled EGR is slightly higher than that of hot EGR strategy [14], [15]. EGR was an effective way of reducing NO*x* to a very low concentration level below 1ppm along with three-way catalytic converter. EGR technique can produce more torque than lean-burn fuel metering strategy if

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low NO*x* emissions are a requirement. However, if NO*x* emissions are not a concern, the lean-burn strategy can produce more torque than the EGR strategy [16], [17]. In general EGR can improve fuel economy, reduce NO*x* emission and prevent the tendency of the engine towards knock. However, the maximum possible EGR rate is limited by high cyclic variations, misfire and decrease in total efficiency.

In this study, hydrogen is selected as the test fuel and the load and EGR rate are varied to study the performance, combustion and emissions of a hydrogen-fueled SI engine

2 Experimental Setup

The specifications of the test engine are listed in Table 1. The schematic diagram of the engine and control system is shown in Fig. 1.

TABLE 1
Specifications of the Test Engine

Engine make	Greaves Cotton
Engine type	Single cylinder, Four stroke
Power	2.2 kW
Speed	3000 rpm
Bore	70 mm
Stroke	67.7 mm
Displacement	256 CC
Compression Ratio	10.3 : 1

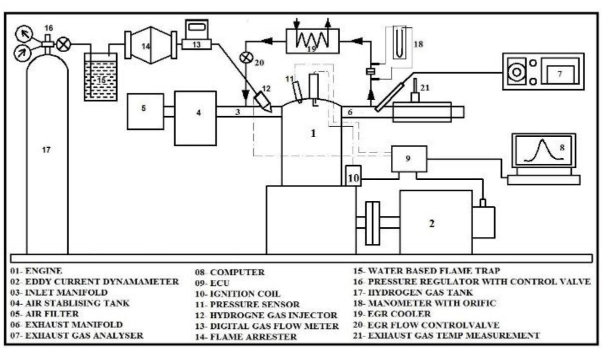

Fig. 1. Schematic view of the experimental setup.

The gasoline engine was modified to equip with hydrogen fuel by using a gas injector mounted on the inlet manifold. The hydrogen supplying system of the engine consists of a hydrogen tank, a pressure regulator, flame arrester, digital gas flow meter and a hydrogen injector as shown in Fig. 2. Table 2 shows the properties of hydrogen fuel.

Fig. 2. Photographic view of Hydrogen flow line setup.

TABLE 2
Properties of Hydrogen Fuel

Property	Values
Limits of flammability in air, vol. %	4-75
Minimum energy for ignition, mJ	0.02
Quenching gap in NTP air, mm	0.64
Auto ignition temperature, K	858
Stoichiometric air fuel ratio	34.4
Laminar flame speed at NTP, m/s	1.90
Diffusion coefficient in NTP air, cm^2/s	0.61
Heat of combustion (LCV), MJ/kg	119.93

An electronic control unit was used to control the injection timing, duration and spark timing. The hydrogen used in this study has a purity of 99.99% at a pressure of 140 bar in the tank which can be reduced to 3 bar by a double-stage pressure regulator.

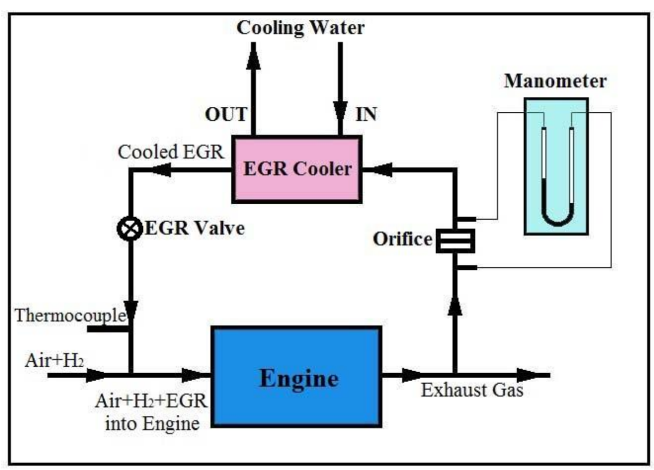

Fig. 3. Schematic diagram of the EGR control system.

In this study, the EGR rate is manually controlled by the EGR valve. The schematic diagram of an EGR control system is shown in Fig. 3. The exhaust gas is introduced into the in-

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take manifold, through the EGR cooler, flow meter and the EGR valve. The cooling water supplied to the EGR cooler can be varied to maintain the EGR outlet temperature between 45 and 50°C. The partially cooled exhaust gas enters the intake pipe to mix with the fresh charge. Different EGR rates can be adjusted by using the EGR valve.

A Horiba MEXA-534L analyzer was used to measure the exhaust species such as HC, CO and CO_2 concentration with the measuring accuracy of 12 ppm for HC, 0.06% for CO, 0.5% for CO_2 and 10 ppm for exhaust NO*x* concentration. Cylinder pressure was recorded by a Kistler piezoelectric transducer with the resolution of 10 Pa, and the dynamic top-dead-center (TDC) was determined by motoring. The crank angle signal was obtained from a Kistler crank angle encoder mounted on the main shaft, while the information of pressure and crank angle was recorded by Legion Brother's data acquisition system. The signal of cylinder pressure was acquired for every 0.1 crank angle, and the acquisition process covered 120 completed cycles, whose average value was outputted as the pressure data used or the calculation of combustion parameters.

3 EXPERIMENTAL PROCEDURE

The test was carried out at an engine speed of 3000 RPM and wide open throttle (WOT) for all load conditions and EGR rate. The hydrogen injection timing, duration and spark timing can be controlled and altered via the commands from a calibrated computer by using various engine sensor signals acquired from the ECU. K-type thermocouples were installed at various locations such as inlet manifold, exhaust manifold, EGR inlet, EGR outlet, EGR cooling water inlet and outlet, spark plug, and lubricating oil sump which are used to record the temperatures with an accuracy of ±1°C. As it is widely known, spark timing has a great influence on engine performance. For each testing point, the minimum spark timing for best torque (MBT) was maintained in all test conditions. In the experiment, the species of exhaust gases and various performance and combustion parameters were measured when the engine is operating at steady operating conditions. The engine performance, combustion, and emissions parameters for different EGR rates and various loads from 0 to 100% were compared and analysed. During the experiment, the lubricant oil temperatures were maintained between 90 and 95°C ±1°C to reduce its bad effect on the experimental results.

4 EVALUATION OF % EGR RATE

Only small traces of CO_2 is present in the exhaust gas because of lubrication oil combustion in case of pure hydrogen-fueled SI engine. So, it is not possible to use the standard practice of obtaining the amount of recirculated exhaust gases from the CO_2 concentration in the intake and exhaust of the engine running with pure hydrogen. Another method of measuring the EGR rate is to measure the mass flow rate of air before and after EGR supplied to the engine. The decrease in the measured air flow rate is caused by the EGR flow rate by displacing some amount of air by EGR, so this can be used to determine the exact quantity of EGR [18], [19].

The percentage of exhaust gases recirculated back to the engine intake (% EGR rate) is as follows:

$$\%\,EGRrate = \frac{\dot{m}\;EGR}{\dot{m}\;Air + \dot{m}\;EGR} \qquad (1)$$

where $\dot{m}$EGR and $\dot{m}$Air are the mass flow rates of exhaust recirculated gas and air respectively. As shown in (1), EGR rate here represents the portion of EGR gas occupied in total incoming mixture regardless of engine displacement.

5 RESULTS AND DISCUSSION

The engine performance and emission data were measured for various EGR rates say 0%, 10%, 20% and 30% with different load conditions were analysed and presented graphically for thermal efficiency, brake-specific fuel consumption, exhaust gas temperature, volumetric efficiency, HC, CO and NO*x* emissions.

5.1 Brake-Specific Fuel Consumptions

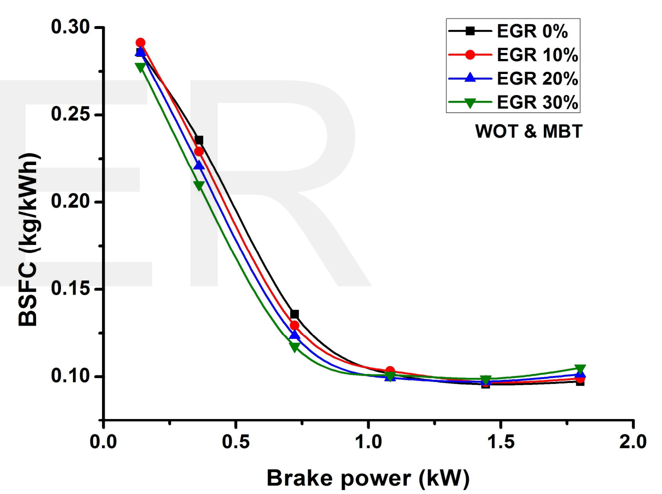

Fig. 4. Variations of brake-specific fuel consumption with brake power.

Fig. 4 shows the variations of brake-specific fuel consumption (BSFC) with brake power. BSFC is lower at lower loads for an engine operated with EGR compared to 0% EGR rate. However, at peak engine loads, BSFC with 30% EGR rate is slightly higher than 0% EGR rate. At higher loads, the amount of fuel supplied to the cylinder is increased at higher rate and oxygen available for combustion gets reduced. Thus, the air-fuel ratio is changed and this increases the BSFC.

5.2 Brake Thermal Efficiency

The variations of thermal efficiency with brake power are shown in Fig. 5. The brake thermal efficiency is found to have slightly increased with the EGR rate at lower engine loads. The brake thermal efficiency for 30% EGR rate is 15.83% higher than 0% EGR at lower loads corresponding to a power of 1.6kW. However, it is 7.3% lower than 0% EGR rate at maxi-

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mum load condition with 1.8 kW power. At higher EGR rate, brake thermal efficiency is significantly dropped at peak load, because with the increase in EGR rate, the specific heat capacity is increased and combustion temperature is decreased by dilution, and this will decrease the mixture burning velocity and increase the combustion duration. Engine power decreases and combustion duration increases due to the more introduction of EGR rate say more than 30%. So the test was conducted between 0 to 30% of EGR rate.

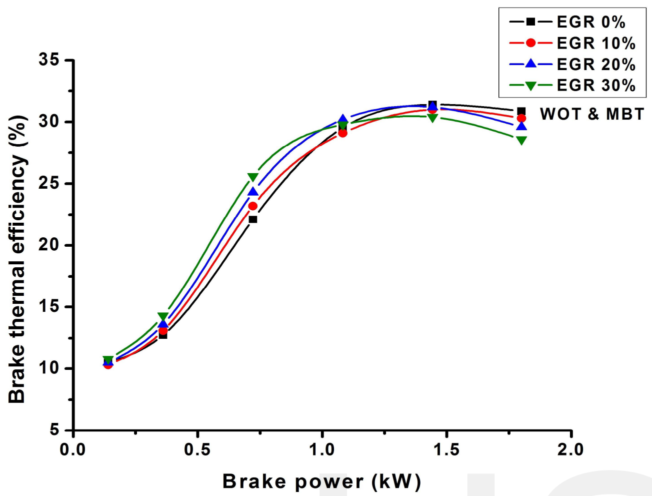

Fig. 5. Variations of brake thermal efficiency with brake power.

5.3 Exhaust Gas Temperature

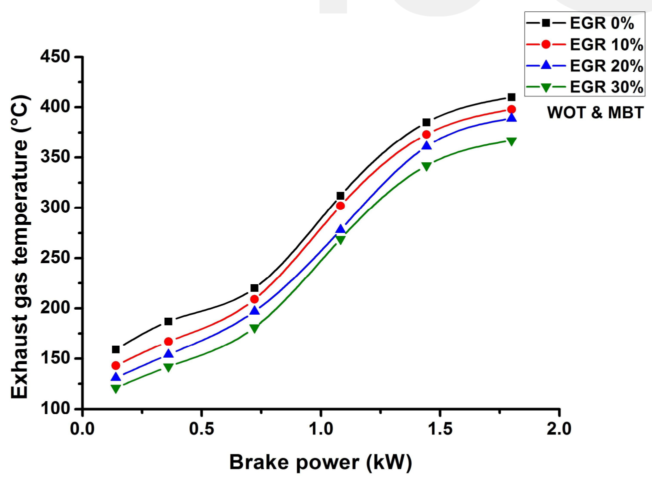

Fig. 6. Variations of exhaust gas temperature with brake power.

Fig. 6 represents the comparison of exhaust gas temperature with the brake power. It has been observed that the exhaust gas temperature increases with the increase in brake power. Also exhaust gas temperature decreases with the increase in EGR rate. When the engine is operated with EGR, the temperature of exhaust gas is significantly lower than the temperature of exhaust gas without EGR under all load conditions. The reasons for temperature reduction is dilution of EGR with fresh mixture causes higher specific heat of the intake air mixture and relatively lower availability of oxygen for combustion.

5.4 Volumetric Efficiency

Fig. 7 represents volumetric efficiency for different EGR rates with brake power. The volumetric efficiency is the ratio of the actual mass of mixture in the combustion chamber to the mass of mixture that the displacement volume could hold if the mixture was at ambient density.

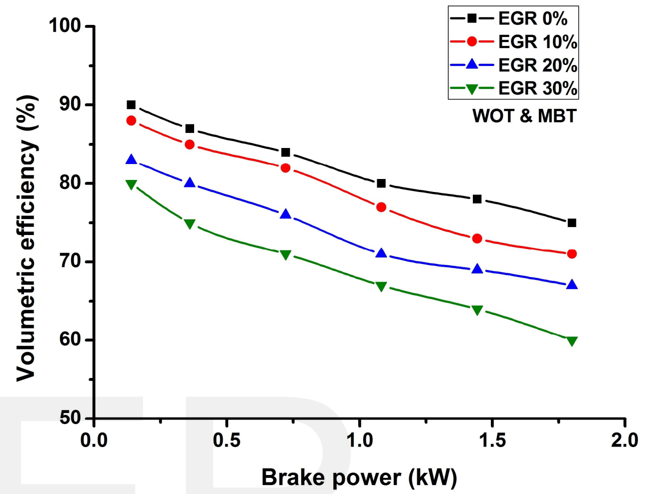

Fig. 7. Variations of volumetric efficiency with brake power.

Hydrogen being lighter than air displaces the air. The volumetric efficiency decreases with the increase in load. The hydrogen gas can take considerably more space in the cylinder, leaves less volume for the air being pumped into the cylinder. This causes a drastic reduction in volumetric efficiency while the load increases in hydrogen engine. It can be also found that as the EGR rate increases, volumetric efficiency decreases. The intake air mass flow reduces because of EGR implementation and this means the volumetric efficiency also drops with the increase in EGR rate.

5.5 Hydrocarbon and Carbon monoxide Emissions

Variations of hydrocarbon (HC) and carbon monoxide (CO) with brake power are shown in Figs. 8 and 9, respectively. Hydrogen fuel is the only non-carbonaceous fuel available on the earth. HC and CO emissions are produced in the hydrogen engine only due to the combustion of lubricating oil in the combustion chamber. The hydrocarbon emission level present in the exhaust gas is very low because of the absence of carbon in the hydrogen fuel. It is observed from the graph that when brake power increases HC emission also increases. HC is seen very low for lower loads and it increases at higher loads. HC emission for 30% EGR is 23% higher than 0% EGR rate at peak load. It is also found that very little variation of CO emission was seen.

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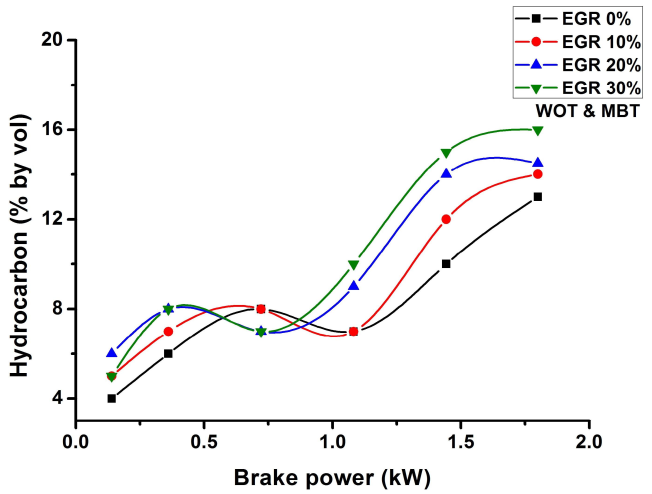

Fig. 8. Variations of hydrocarbon with brake power.

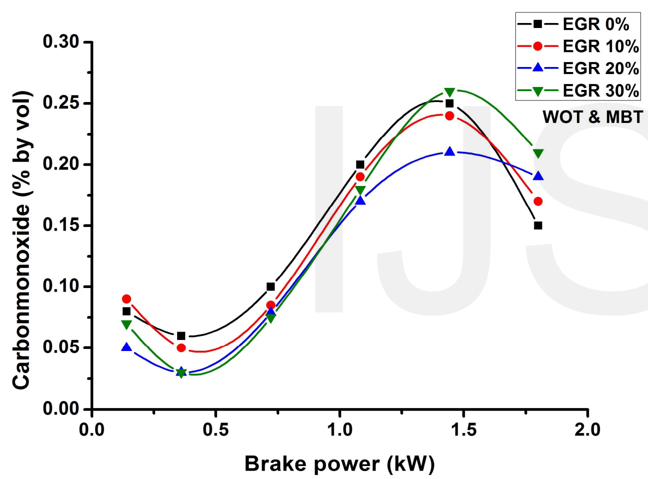

Fig. 9. Variations of carbon monoxide with brake power.

5.6 Oxides of nitrogen

Fig. 10 shows the main benefit of EGR in reducing NO*x* emissions. NO*x* emission is higher during higher loads and very low at lower load conditions. In general, the increase in the amount of the EGR rate leads to a great reduction in the NO*x* emissions. Even at 10% EGR rate is sufficient to cause a significant drop in the NO*x* emissions. The degree of reduction in NO*x* at higher loads is higher. The peak NO*x* value reached at 1.44 kW is about 5890 ppm for 0% EGR rate and it is significantly drops to 1590 ppm for 30% EGR. The maximum NO*x* reduction reached 73% at 30% EGR rate. The reasons for reduction in NO*x* emissions using EGR have reduced oxygen concentration and decreased flame temperatures in the combustible mixture. This indicates that the percentage EGR rate has a significant effect on NO*x* formation rates.

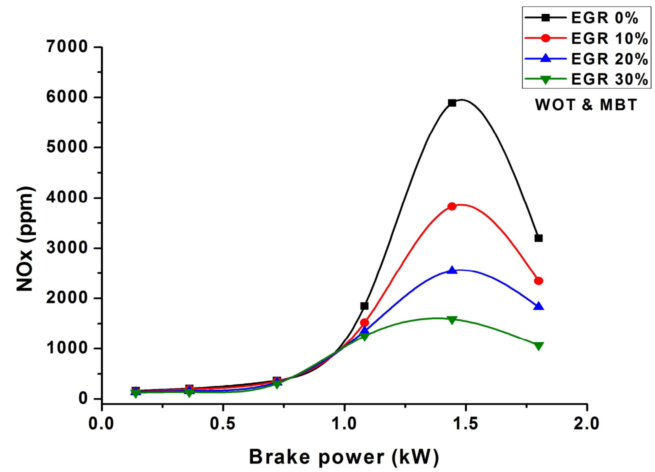

Fig. 11. Variations of oxides of nitrogen with brake power.

5.7 Cylinder Pressure

Fig. 11 shows the effects of the percentage of EGR dilution in the inlet mixture on in-cylinder pressure at peak load with MBT spark timing. The maximum cylinder pressure decreases with the increase in EGR rate. The crank angle at which the maximum cylinder pressure occurs is further shifted away from TDC with the increase of EGR rate. This can confirm that EGR dilution is capable of reducing in-cylinder stresses, and consequently, it can be used to suppress abnormal combustion occurrence such as surface ignition and knock. The peak cylinder pressure with 0% EGR is 34.37 bars. When the inlet mixture was diluted with 30% EGR rate, the maximum cylinder pressure decreased by about 14.4 % as it decreased from 36.25 to 29.41 bar as shown in Fig. 11.

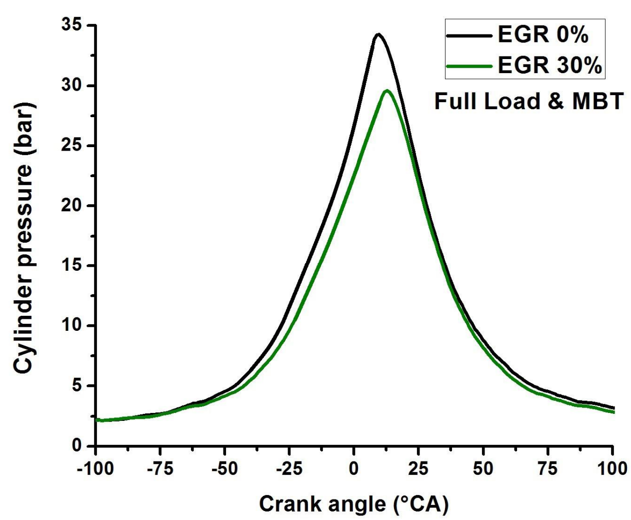

Fig. 11. Variations of cylinder pressure with crank angle.

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5.8 Heat Release Rate

Fig. 12 shows the effect of EGR dilution in the inlet mixture with the heat release rate. It can be noted from Fig. 12 that the maximum heat release rate decreases with the increase in percentage of EGR dilution. The maximum heat release rate is 62.34 J/°CA and 45.33 J/°CA for 0% EGR and 30% EGR rate respectively. Also, the crank angle at which the maximum heat release rate occurs is shifted away further from the TDC with the 30% EGR dilution. The increase in EGR dilution in the inlet mixture decreases the in-cylinder oxygen concentration, and consequently, it reduces the heat release rate.

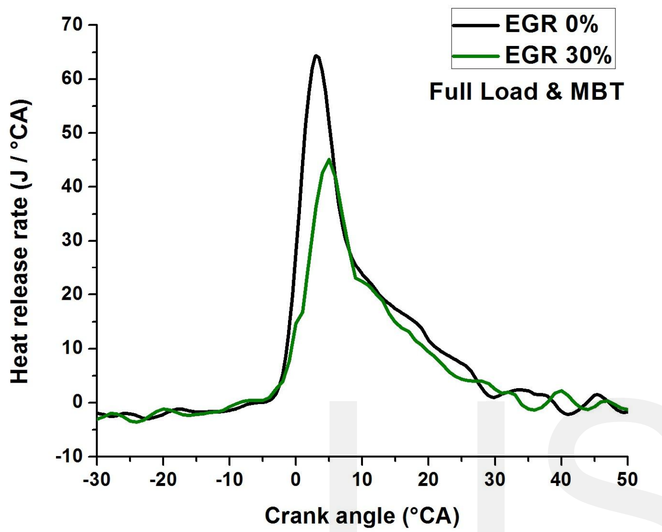

Fig. 12. Variations of heat release rate with crank angle.

6 Conclusions

The overall objective of this work is to investigate the effect of EGR rate on performance, combustion and emission of hydrogen fueled engine. The conclusion drawn from the study is summarized below.

An increase in brake thermal efficiency by about 15.83% during lower load conditions with 30% EGR rate. However, it was dropped by 7.3% during the peak load condition as compared to 0% EGR rate.

BSFC is lower at lower loads for engine operated with higher EGR rates in comparison with 0% EGR rate. Moreover, at peak engine load, BSFC with 30% EGR rate is marginally higher than 0% EGR rate.

Increase in EGR rate lead to reduce both maximum cylinder pressure and heat release rate.

The increase in EGR rate in the inlet mixture decreases both the maximum cylinder temperature and oxygen concentration which leads to a significant reduction in NO*x* emission. The 73% of NOx emission reduction occurs when the EGR rate was increased from 0-30% at 1.44 kW power.

The increased EGR rate leads to little increase in HC and CO emissions. Moreover, CO emission is negligible in magnitude with pure hydrogen-fueled engine.

In general, it can be concluded that the use of EGR is an effective method for the reduction of backfire, engine knock and NO*x* emissions at the minimal loss of engine efficiency at 30% EGR rate and the NO*x* emissions reduced by about an order of 73% when EGR levels were increased from 0 to 30%.

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