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Influence of oxygen enriched hydrogen gas as a combustion catalyst in a DI diesel engine operating with varying injection time of a diesel fuel

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Influence of oxygen enriched hydrogen gas as a combustion catalyst in a DI diesel engine operating with varying injection time of a diesel fuel

Abstract

Automobiles give out more pollutants. These pollutants become a bigger threat to our environment. This study examines the influence of oxygen enriched hydrogen (OEH) gas as a combustion catalyst in a DI diesel engine operating with varying injection time of a diesel fuel. For this study the OEH gas was produced by the process of electro-chemical dissociation of water. The OEH gas of 4.6 litre per minute (lpm) was aspirated into the engine cylinder along with intake air, at varied injection times of the diesel fuel. Three injection times were selected. One was the standard injection time of 23^{o}BTDC (Before Top Dead Centre) recommended by the engine manufacturer, second one was the retarded injection time of 19^{o}BTDC and the third one was the advanced injection time of 27^{o}BTDC. When OEH gas was inducted at 100% rated load of the engine at standard injection time, the brake thermal efficiency increased by 16.45% and the emissions of oxides of nitrogen (NO_X) increased by 16.9%. All other engine-out emissions like carbon monoxide (CO), unburned hydrocarbon (UBHC) and smoke got reduced by 15.38%, 19.7% and 28.57% respectively, compared to diesel combustion. At advanced injection time, the brake thermal efficiency and the NO_X emission got increased by 19.03% and 21.42%. Other engine-out emissions like CO, UBHC and smoke got reduced by 11.53%, 22.72% and 30.95% respectively. However, in retarded injection time, the brake thermal efficiency increased by 12.21% and engine-out emissions like CO, UBHC, NO_X and smoke got reduced by 7.69%, 12.12%, 9.04% and 19.04% respectively. From the data, it is evident that the diesel engine can be operated efficiently by using OEH gas as a combustion catalyst with the optimized injection timing of diesel fuel.

Keywords: diesel engine; electro-chemical dissociation; oxygen enriched hydrogen (OEH) gas; standard injection time; retarded injection time; advanced injection time; engine-out emissions

1. INTRODUCTION

Day by day our environment gets degraded because of various pollutants coming out from various sources. To reduce the same, numerous methods have been researched. One of the methods is using alternative fuels in automotives. Alternative fuels are comparatively clean fuels.[1] Hydrogen is emerging as one of the favorite alternative fuels. It also acts as an energy carrier. The properties of hydrogen which make it an eligible automotive fuel are: low ignition energy, low density, wide flammability limit, high diffusivity, and high flame speed.[2] Due to its wider flammability limit, it can burn lean mixtures comfortably resulting in fewer amounts of exhaust emissions. Currently, hydrogen is produced by the method of steam reforming and partial oxidation of hydrocarbons.[3] However, for relatively small hydrogen quantities or high purity hydrogen is required, processes such as water electrolysis, ammonia decomposition and methanol reforming are used.[4] Hydrogen can be generated by splitting water. Various techniques used to split the water are electrolysis, plasmolysis, magnetolysis, thermal approach, use of light, bio-catalytic decomposition, and radiolysis.[5]

When hydrogen is supplemented into the combustion process, the in-cylinder pressure and the thermal efficiency get increased.[6] This substantial improvement in combustion is due to the fast and clean burning characteristics of hydrogen in comparison to conventional fuels.[7] Increased flame speed of hydrogen reduces the engine-out emissions.[8]

Numerous studies have previously reported on hydrogen combustion in diesel engines in different conditions. The combustion process of a diesel engine can be enhanced by supplementing a small amount of hydrogen to the diesel fuel.[7]

In 1820, Cecil[9] wrote a paper on the design and construction of hydrogen engine; and how hydrogen energy could be utilized effectively. Most likely, this is the most primitive development made in hydrogen-fueled engines. Properties of hydrogen are listed in **Table 1**. Some researchers tried to use hydrogen as a sole fuel in the diesel engine. The self-ignition temperature of hydrogen is 858 K.[10] It is impractical to ignite hydrogen, just by heat of compression. It needs assistance to start its combustion. Wong[11] used ceramic glow plug as an ignition starter.

The dual-fuel engine operating with hydrogen consumes less fuel than a pure diesel operating engine resulting in a lower level of smoke emission.[12] This method of operation enables full realization of higher brake thermal efficiency. But, it creates the storage problem of hydrogen. One of the feasible solutions to this problem is to generate hydrogen on-board. One of the processes which assist the on-board generation of hydrogen is electro-chemical dissociation of water. The addition of oxygen to the air-fuel mixture considerably enhances brake thermal efficiency and significantly lessens emissions in the exhaust.[7] Santilli[13] in his analysis gave various measurement techniques to find the compositions of a mixture of hydrogen and oxygen gas produced via an electrolyzer. This mixture was appreciably different from other known gas mixtures. Bari and Esmaeil[14] did their experimental work in a four-cylinder, direct injection, water-cooled diesel engine. H_2/O_2 mixture produced by water electrolysis was inducted into the cylinder at various load conditions of the engine. Their result showed that at 19 kW of load, the brake thermal efficiency increased from 32% to 34.6%. HC emission decreased from 187 ppm to 85 ppm. Least amount of carbon dioxide (CO_2) of 2.06 ppm was also observed. However, NO_X emission increased from 220 ppm to 280 ppm. Yilmaz *et al.*[15] investigated the effect of hydroxy gas on emission and performance characteristics of a four cylinder, four stroke compression ignition engine. They produced the hydroxy gas by the process of electrolysis. The result of their investigation showed that hydroxy gas addition to the engine without any modification resulted in increasing engine torque output by an average of 19.1%, reducing CO emissions by an average of 13.5%, HC emissions by an average of 5% and SFC by an average of 14%. Birtas *et al.*[16] carried out a test on a naturally aspirated direct injection, tractor diesel engine with four cylinders in-line having the total capacity of 3759 cm^3. The hydrogen rich gas (HRG) produced by the water electrolysis process was aspirated along with the air stream inducted into the engine cylinder. The result showed that by adding HRG, smoke reduced up to 30% while NO_X concentrations increased up to 14% compared to pure diesel operation.

Injection timing plays an important role in reducing the engine-out emissions. A number of studies by several researchers indicate its significance. Shioji and Mohammadi[17] carried out an investigation on diesel engine performance and emission characteristics when LCG (Low Calorific Gases) and LCG with small portion of hydrogen was inducted into the inlet manifold of four-stroke single cylinder naturally aspirated direct-injection diesel engine with varied injection time of diesel fuel. They varied the injection timing of diesel fuel in the range of 7.5^o BTDC to 15^o BTDC at the engine load of 0.6 MPa. Their results indicated that advancing injection timing improved thermal efficiency. This trend was similar for both fuels. This advancement in injection timing also improved smoke, THC and CO emissions but the NO_X emission got worsened along with almost same thermal efficiency as diesel fuel operation.

When going through a vast literature of hydrogen usage in diesel engines, it was noted that vital work had not been carried out in optimizing the usage of OEH gas in the DI diesel engine. So the author already started his efforts to fill this gap and published research papers in this area.[18-20] To fill further, in this study the effect of OEH gas addition on diesel combustion under variable injection timing of the diesel fuel was analyzed.

2. PRESENT EXPERIMENTAL METHOD

The present method provides a practical solution for onboard production of hydrogen. It avoids storing of hydrogen in heavy pressurized storage tanks. In the current process, the hydrogen was produced with oxygen at the desired rate by the electro-chemical dissociation of water. An electrolyzer dissociated the aqueous electrolytic solution consists of water and electrolyte into a new mixture of gas. This gas mixture consisted of single atoms of H and O called atomic hydrogen and oxygen, dual molecules of H_2, O_2 and H_2O.[13] This mixture was named OEH gas. The generated gas was aspirated into the engine cylinder along with intake air at varied injection timings of diesel fuel. Three injection times were selected. One was the standard injection time of 23^o BTDC recommended by the engine manufacturer, second one was the retarded injection time of 19^o BTDC and the third one was the advanced injection time of 27^o BTDC. The injection times were varied by modifying the shim thickness at the link point between the pump and the engine.[21] In this experiment, petroleum diesel combustion with standard injection time of 23^{o}BTDC was taken as a base line to compare efficiency of the test engine at different injection times of the diesel fuel operating under the influence of OEH gas with a flow rate of 4.6 lpm at different load ranges of the test engine. All the experimental data were collected after the engine reached the steady state.

3. TEST ENGINE SETUP

The present experimental investigation was conducted in a Kirloskar make single cylinder, water-cooled, four stroke, DI diesel engine, developing a rated power of 5.9 kW at a speed of 1800 rpm and having a compression ratio of 17.5:1. The detailed engine specification is given in **Table 2.** The experiments were conducted at a constant speed of 1800 rpm with variable load. The load ranged from no load condition to full load condition (0% to 100% rated load of the engine with the steps of 25%). The operating parameters such as injection time of diesel fuel and injection pressure of the diesel fuel recommended by the manufacturer are 23^o BTDC and 200 bar injection pressure. The governor of the engine was used to control the engine speed. Eddy current dynamometer was coupled to the engine for its loading. The flow of OEH gas was controlled by digital mass flow controller of Aalborg make. The in-cylinder pressure of the engine was measured with a Kistler make piezoelectric pressure transducer of air cooled type. K type thermocouples were used to measure the cooling water temperature, inlet air temperature, and the exhaust gas temperature. Crypton 290 EN2 five gas analyzer was used to measure the exhaust gas emissions such as CO, CO_2, UBHC, NO_X and excess oxygen. AVL smoke meter was used to measure the smoke in terms of Hatridge Smoke Unit (HSU). The schematic arrangement of the experiment is shown in the **Figure1**.

4. EXPERIMENTAL PROCEDURE

When DC power of 12V was supplied, the potential difference between the anode electrodes and the cathode electrodes along with the aqueous electrolyte solution of NaOH present in the electrolyzer generated OEH gas by the process of electro-chemical dissociation of water. The generated gas was then passed through a drier, flashback arrestor and flame trap before mixing with inlet air. The drier was used to remove the moisture content present in the gas. Flashback arrestor and flame trap were used to suppress the flame if a backfire from the engine occurred.

5. EXPERIMENTAL UNCERTAINTY

In the present experimental investigation, many physical quantities were measured using various instruments. All the instruments were calibrated prior to their use. Uncertainties for the present experimental work are detailed in **Table 3**. The uncertainties for basic measurements like temperature, speed, time etc., were taken as the value of least count of relevant instruments. The errors on quantities such as CO, CO_2, UBHC, NO_X, O_2, smoke were taken from manuals supplied by the manufactures of instruments. The uncertainty for derived quantities was computed on the basis of Holman's method.[22] This was based on the work of Kline and McClintock.[23]

6. RESULT AND DISCUSSION

6.1 Brake thermal efficiency (BTE)

Brake thermal efficiency is the real indication of the efficiency of the engine. It is defined as the degree with which the chemical energy available in the fuel is converted into useful work. The graphical representation of the effect of OEH gas on the brake thermal efficiency at different rated load conditions of a test engine at different injection timings of diesel fuel is shown in **Figure 2**. When OEH gas is used as a combustion catalyst in diesel combustion, the rate of increase in brake thermal efficiency is higher than base line operation. The experimental results showed that under the influence of OEH gas at 100% rated load, the brake thermal efficiency increased by 16.45%, 12.21%, and 19.03% for standard injection timing of 23º BTDC, retarded injection timing of 19º BTDC and advanced injection timing of 27º BTDC compared to base line operation. This increase in brake thermal efficiency is due to higher heat content of the hydrogen present in the gas mixture, its high flame velocity, and the atomic hydrogen and oxygen present in the gas.[13] The atomic hydrogen and oxygen present in the gas are highly energetic and more reactive than their dual molecule counterparts.[20] This intrinsic characteristic enables fissure of the heavier hydrocarbon molecules of diesel fuel and initiates the chain reaction, which results in high-efficiency combustion when the petroleum diesel initiates the ignition.[20] When the test engine was operated in retarded injection time of 19º BTDC with OEH gas, it resulted in 3.63% decrease in brake thermal efficiency compared to standard injection time operation with OEH gas and

5.73% decrease in brake thermal efficiency compared to advanced injection time operation of 27º BTDC with OEH gas. During retarded injection time operation, part of combustion took place during the expansion stroke. This was also confirmed by the in-cylinder pressure curve at this injection time. At 27º BTDC, the maximum brake thermal efficiency was obtained compared to other injection timings. This result confirms the result obtained by Mohammadi *et al*.[24] The brake thermal efficiency increased by 2.22% at advanced injection time of 27º BTDC compared to standard injection time of 23º BTDC.

6.2 Brake specific energy consumption (BSEC)

Figure 3 represents the comparison of BSEC when OEH gas of 4.6 lpm was added in the diesel combustion process at different injection timings of the diesel fuel. The experimental results showed that the BSEC increased when the injection time was retarded and decreased when the injection time was advanced. Under the influence of OEH gas at 100% rated load, the BSEC got decreased by 14.12%, 10.88%, and 15.99% for standard injection timing of 23º BTDC, retarded injection timing of 19º BTDC and advanced injection timing of 27º BTDC compared to base line operation. Dulger and Ozcelik[25] reported that by using on-board hydrogen, the fuel consumption and the engine-out emissions could be reduced and they attributed this decrease in BSEC to high catalytic nature of hydrogen gas. This resulted in uniformity in fuel-air mixture formation and extraction of more energy from the diesel fuel. When the test engine was operated in retarded injection time of 19º BTDC, it resulted in 3.77% increase in BSEC compared to standard injection time operation and 6.08% increase in BSEC compared to advanced injection time operation of 27º BTDC. This might be due to shorter ignition delay period[24] which resulted in low efficiency combustion. At 27º BTDC, the minimum BSEC was obtained compared to other injection timings. The BSEC got decreased by 2.22% at advanced injection time of 27º BTDC compared to standard injection time of 23º BTDC. This might be due to participation of more homogeneous mixture of fuel and air in the combustion process which resulted in improved combustion.

6.3 Carbon monoxide emission (CO)

Figure 4 depicts the comparison of CO emission for petroleum diesel and diesel with OEH gas of 4.6 lpm at different injection timings of diesel fuel. When the test engine was operated in retarded injection time of 19º BTDC at the rated load of the test engine, it resulted in 9.09% and 4.34% increase in CO emission compared to 23º BTDC and 27º BTDC. This might be due to under-mixing of fuel and air, some fuel particles in the fuel-rich zones might never react with oxygen. The CO emission got decreased by 7.69%, 15.38%, and 11.53% at 19º BTDC, 23º BTDC, and 27º BTDC compared to base line operation. This might be due to high diffusing property of hydrogen and its high flame velocity resulting in intense combustion. This result confirms the result obtained by Bari and Esmaeil.[14] At 27º BTDC, CO emission got increased by 4.54% compared to 23º BTDC operation.

6.4 Carbon dioxide emission (CO_2)

Figure 5 displays the comparison of CO_2 emission when OEH gas of 4.6 lpm was supplemented in the diesel combustion process at different injection timings of diesel fuel. Advancing the injection time of the diesel fuel increased the CO_2 emission whereas retarding the injection time reduced the CO_2 emission. Under the influence of OEH gas at full rated load of the engine, CO_2 emission got increased by 12.12% and 9.09% for standard injection timing of 23º BTDC and advanced injection timing of 27º BTDC compared to base line operation. This might be due to spontaneous combustion of OEH gas when its ignition was initiated by pilot diesel fuel. When the test engine was operated in retarded injection time of 19º BTDC, it resulted in 5.4% and 2.77% decrease in CO_2 emission compared to 23º BTDC and 27º BTDC. This might be due to improper conversion of CO to CO_2 due to decrease in combustion temperatures and resulted in less intense combustion. At 23º BTDC, the maximum CO_2 emission was emitted from the engine compared to other injection timings. The CO_2 emission got decreased by 2.7% at 27º BTDC compared to 23º BTDC. This might be due to dissociation of CO_2 into CO and excess oxygen. The increase in CO emission at 100% load also justified this.

6.5 Unburned hydrocarbon emission (UBHC)

Figure 6 shows the comparison of UBHC emission when OEH gas of 4.6 lpm was added in the diesel combustion process at different injection timings of diesel fuel. The advancement of injection time lessens the UBHC emission whereas retarding the injection amplifies the same. Under the influence of OEH gas at 100% rated load of the engine, UBHC emission got decreased by 19.7% and 22.72% for standard injection timing of 23º BTDC and advanced injection timing of 27º BTDC compared to base line operation. This might be due to enhanced H/C ratio in the overall fuel mixture. This result confirms the result obtained by Shioji and Mohammadi.[17] At the retarded injection timing of 19º BTDC, UBHC emission got decreased by 12.12% compared to base line operation. When the test engine was operated in retarded injection time of 19º BTDC, it resulted in 9.43% and 13.72% increase in UBHC emission compared to 23º BTDC and 27º BTDC. This might be due to low homogeneity of combustible mixture formed during the ignition delay period. At 27º BTDC, the minimum UBHC emission was exhausted from the engine compared to other injection timings. The UBHC emission got decreased by 3.77% at 27º BTDC compared to 23º BTDC. This might be due to proper mixture formation with enough oxygen to burn all the fuel particles.

6.6 *Oxides of nitrogen emission (NO_X)*

Figure 7 represents the comparison of NO_X emission when OEH gas of 4.6 lpm was added in the diesel combustion process at different injection timings of diesel fuel. The advancement of injection time enhanced the NO_X emission whereas retarding the injection helped to reduce the same. Under the influence of OEH gas at 100% rated load, NO_X emission increased by 16.9% and 21.42% for standard injection timing of 23º BTDC and advanced injection timing of 27º BTDC compared to base line operation. This might be due to enhanced pre-mixed burning phase[26] as a result of instantaneous combustion of OEH gas when it was ignited by pilot diesel fuel. The heat release rate curve shown in Figure 11 also confirmed this. This result confirms the result obtained by Tomita *et al.*[26] who investigated the effect of hydrogen injection in a single cylinder, four-stroke diesel engine by varying the injection timing of light oil from 60° BTDC to 5° ATDC. Their results showed that when the injection timing of the light oil was near 25° BTDC, the NO_X emission got increased and had the maximum value. In the present experiment at the retarded injection timing of 19º BTDC, NO_X emission got decreased by 9.04% compared to base line operation. When the test engine was operated in retarded injection time of 19º BTDC, it resulted in 22.19% and 25.09% decrease in NO_X emission compared to 23º BTDC and 27º BTDC. This might be due to low temperature atmosphere prevailing in the combustion chamber as less time was available to form homogeneous mixture during the ignition delay period which resulted in a drop in the combustion temperature.[27] At 27º BTDC, the maximum NO_X emission occurred in the engine compared to other injection timings. The NO_X emission increased by 3.86% at 27º BTDC compared to 23º BTDC. This might be due to increase in the ignition delay period.[26] When the start of fuel injection timing was earlier, the initial air temperature and pressure would be lower. This caused ignition delay period to increase which in-turn increased the premixed burning phase, the cylinder gas temperature and the NO_X emissions.[28]

6.7 Smoke emission

Figure 8 displays the comparison of smoke emission when OEH gas of 4.6 lpm was added in the diesel combustion process at different injection timings of the diesel fuel and petroleum diesel combustion at standard injection timing. The experimental results showed that the smoke emission got increased when the injection time was retarded and got decreased when the injection time was advanced. Under the influence of OEH gas at 100% rated load of the engine, the smoke emission decreased by 28.57%, 19.04%, and 30.95% for standard injection timing of 23º BTDC, retarded injection timing of 19º BTDC, and advanced injection timing of 27º BTDC compared to base line operation. This result confirms the result obtained by Birtas *et al.*[16] When the test engine was operated in retarded injection time of 19º BTDC, it resulted in 13.33% increase in smoke emission compared to standard injection time operation and 17.24% increase in smoke emission compared to advanced injection time operation of 27º BTDC. When injection time of diesel fuel was retarded, the regions of the better air/fuel mixing got decreased. This in-turn decreased the pre-mixed combustion phase[24] and heat release rate. At 27º BTDC, the minimum smoke emission was obtained compared to other injection timings. The smoke emission got decreased by 3.33% at advanced injection time of 27º BTDC compared to standard injection time of 23º BTDC. When the diesel fuel was injected at advanced injection time, the fuel got sufficient time to mingle with air molecules.[26] This resulted in formation of more homogeneous mixture of fuel and air.[26] When this mixture got ignited, the combustion resulted in less smoke emission compared to other injection timed operations.

6.8 Excess oxygen emission

Figure 9 depicts the comparison of excess oxygen emission for petroleum diesel and diesel with OEH of 4.6 lpm at different injection timings of diesel fuel. The experimental results showed that the excess oxygen emission increased when injection timing was retarded and decreased when injection timing was advanced. When the test engine was operated in retarded injection time of 19º BTDC at the rated load of the test engine, it resulted in 1.19% and 6% increase in excess oxygen emission compared to 23º BTDC and 27º BTDC. This might be due to existence of more fuel-rich zones at this injection timed operation. The excess oxygen emission decreased by 7.78%, 8.87%, and 13.01% at 19º BTDC, 23º BTDC, and 27º BTDC respectively compared to base line operation. This might be due to high diffusion co-efficient of hydrogen present in the gas mixture and its low activation energy resulting in efficient combustion.[29] This confirms the result of Avadhanula *et al*.[30] investigation on hydrogen fueled engine. At 27º BTDC, the excess oxygen emitted from the engine was lower when compared to other injection timed operations. The excess oxygen available at the exhaust of the engine at the advanced injection time of 27º BTDC got decreased by 4.54% compared to 23º BTDC operation. This might be due to the occurrence of more molecular collisions during the combustion at this injection timed operation than other injection timed operations.

6.9 Exhaust gas temperature (EGT)

Figure 10 illustrates the comparison of EGT of petroleum diesel combustion and when OEH gas of 4.6 lpm was added in the diesel combustion process at different injection timings of the diesel fuel. Advancing the injection time facilitated to reduce EGT whereas retarding the injection time augmented the same. Under the influence of OEH gas at the maximum load of the test engine, EGT increased by 6.41% and 4.61% for standard injection timing of 23º BTDC and advanced injection timing of 27º BTDC compared to base line operation. This might be due to enhanced premixed burning phase as a result of spontaneous combustion of OEH gas which increased the average cylinder temperature. At the retarded injection timing of 19º BTDC, EGT got increased by 8.71% compared to base line operation. When the test engine was operated in retarded injection time of 19º BTDC, it resulted in 2.16% and 3.92% increase in EGT compared to 23º BTDC and 27º BTDC injection timed operations. This might be due to improper expansion of combustion gases as little time was available for expansion. This result confirms the result obtained by Fathi *et al*.[27] in their CFD analysis of hydrogen fueled engine. At 27º BTDC, the minimum EGT was exhausted from the engine compared to other injection timings. The EGT decreased by 1.68% at 27º BTDC compared to 23º BTDC. The peak pressure was achieved at around 362 degree crank angle for 27º BTDC combustion. This facilitated more complete expansion of combustion gases when compared to other injection timed operations. The heat release curve at this injection time also confirmed this statement.

6.10 Heat release rate (HRR)

Figure 11 compares heat release rate with crank angle when OEH gas of 4.6 lpm was inducted in the diesel combustion process at different injection timings of diesel fuel at rated load of the engine. The advancement of injection time augmented the heat release rate whereas retarding the injection time helped to decrease the same. Under the influence of OEH gas of 4.6 lpm at 100% rated load of the engine, the heat release rate increased by 13.75% and 16.25% for standard injection timing of 23º BTDC and advanced injection timing of 27º BTDC compared to base line operation. This might be due to more constant volume combustion. This led to enhanced premixed combustion phase. This result confirms the result obtained by Tomita *et al.*[26] At the retarded injection timing of 19º BTDC, the heat release rate decreased by 7.5% compared to base line operation. When the test engine was operated in retarded injection time of 19º BTDC, it resulted in 18.68% and 20.43% decrease in heat release rate compared to 23º BTDC and 27º BTDC operations respectively. When the engine was operated in a retarded injection time of diesel fuel, the fuel was introduced into the cylinder at comparatively higher pressure and temperature environment. Owing to this, the ignition delay period and the pre-mixed combustion phase got reduced[24]. At 27º BTDC, the maximum heat release rate was obtained compared to other injection timings. The heat release rate increased by 2.19% at 27º BTDC compared to 23º BTDC. This might be due to the elevated flame temperature and less heterogeneous fuel-air mixture at this injection timed operation.

6.11 In-cylinder pressure

Figure 12 compares in-cylinder pressure with crank angle when OEH gas of 4.6 lpm was inducted in the diesel combustion process at different injection timings of diesel fuel at rated load of the engine. Advancing the injection time of diesel fuel amplified the peak in-cylinder pressure whereas retarding the injection time helped to decrease the same. When OEH gas of 4.6 lpm was introduced to diesel combustion at 100% rated load, the peak in-cylinder pressure got increased by 5.71% and 10.72% for standard injection timing of 23º BTDC and advanced injection timing of 27º BTDC compared to base line operation. This might be due to enhanced pre-mixed burning phase. When the pre-mixed burning was enhanced, flame propagation through the hydrogen-air mixture led to rapid heat release rates, increased the peak cylinder pressure and temperature, and improved brake thermal efficiency.[31] At the retarded injection timing of 19º BTDC, the peak in-cylinder pressure got decreased by 2.85% compared to base line operation. When the test engine was operated in retarded injection time of 19º BTDC, it resulted in 8.1% and 12.25% decrease in peak in-cylinder pressure compared to 23º BTDC and 27º BTDC. At 27º BTDC, the maximum peak in-cylinder pressure was obtained compared to other injection timings. The peak in-cylinder pressure increased by 4.72% at 27º BTDC compared to 23º BTDC. The peak in-cylinder pressure primarily depends on mixing rate, temperature and availability of oxidants like OH and oxygen radicals. At the injection time of 27º BTDC, all these facts were more pronounced and resulted in a more homogeneous mixture and efficient combustion.

7. CONCLUSION

The results of the present study distinctly show that the DI diesel engine performance can be enhanced and all engine-out emissions can be reduced by using OEH gas as a combustion catalyst in diesel combustion with change in injection timing of a diesel fuel. Some of the important conclusions drawn from the present experimental study are presented in this section. The optimized injection timing of the diesel fuel is 19° BTDC when 4.6 lpm of OEH gas is used as a combustion catalyst in diesel combustion. When OEH gas of 4.6 lpm was inducted at 100% rated load of the engine with diesel injection timing of 23° BTDC, 27° BTDC, and 19° BTDC, the brake thermal efficiency, increased by 16.45%, 19.03% and 12.21% respectively compared to base line operation. This might be due to high catalytic nature OEH gas, which enhances the overall combustion phenomena. The NO_X emission got increased by 16.9% and 21.42% for the injection timing of 23° BTDC and 27° BTDC. But, when the injection timing was retarded to 19° BTDC, it got reduced by 9.04%. The smoke emission got reduced by 28.57%, 30.95%, and 19.04% for the injection timing of 23° BTDC, 27° BTDC, and 19° BTDC respectively. The UBHC emission got reduced by 19.7%, 22.72%, and 12.12% for the injection timing of 23° BTDC, 27° BTDC, and 19° BTDC respectively. Use of OEH gas as a combustion catalyst in DI diesel engine combustion results in improvements in performance and reduction in emissions, which can be observed from the above results. In particular, the retarded injection timing of 19° BTDC gives a significant improvement in performance as well as emission characteristics of a test engine compared to base line operation including NO_X emission which was not achieved by other injection timed operations. Based on the overall analysis, it is concluded that the DI diesel engine can be operated comfortably and efficiently by using OEH gas as a combustion catalyst with the retarded injection timing of a diesel fuel.

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Abbreviations

BP	-	Brake power
BSEC	-	Brake specific energy consumption
BTDC	-	Before top dead centre
BTE	-	Brake thermal efficiency
CA	-	Crank angle
CI	-	Compression ignition
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
DI	-	Direct injection
EGT	-	Exhaust gas temperature
H_2/O_2	-	Hydrogen-oxygen
HRG	-	Hydrogen rich gas
HRR	-	Heat release rate
HSU	-	Hatridge smoke unit

LCG - Low calorific gases

lpm - Litre per minute

NaOH - Sodium hydroxide

NO_X - Oxides of nitrogen

OEH - Oxygen enriched hydrogen

UBHC - Unburned hydrocarbon

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Table 1. Important properties of hydrogen[10]

Properties of hydrogen	
Limits of flammability in air	4–75% vol.
Minimum energy for ignition	0.02 mJ
Auto-ignition temperature	858 K
Quenching gap in NTP air	0.064 cm
Burning velocity in NTP air	265–325 cm/s
Diffusion coefficient in NTP air	0.61 cm^2/s
Heat of combustion (LCV)	119.93 MJ/kg

Table 2. Engine specifications

Specifications of test engine	
Make and Model	Kirloskar, SV1
General	4-Stroke / Vertical
Type	Compression Ignition
Number of Cylinder	One
Bore	87.5 mm
Stroke	110 mm
Cubic capacity	661 cc
Clearance Volume	37.8 cc
Compression Ratio	17.5: 1
Rated Output	5.9 kW
Rated Speed	1800 rpm
Combustion Chamber	Hemispherical Open
Type of Cooling	Water Cooled

Table 3. Experimental uncertainties

Variable	**Uncertainty**
Speed	± 1 rpm
Temperature	± 1°
Time	± 0.1 s
Pressure	± 0.6164 %
Brake power	± 0.9434 %
Fuel flow	± 0.7319 %
NO_X	± 10 ppm
CO	± 0.01%
CO_2	± 0.03%
UBHC	± 1 ppm
Smoke	± 1 HSU

Figure captions

Figure 1. Schematic arrangement of experimental setup

Figure 2. Variation of BTE with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

Figure 3. Variation of BSEC with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

Figure 4. Variation of CO with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

Figure 5. Variation of CO_2 with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

Figure 6. Variation of UBHC with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

Figure 7. Variation of NO_X with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

Figure 8. Variation of smoke emission with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

Figure 9. Variation of excess oxygen emission with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

Figure 10. Variation of EGT with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

Figure 11. Variation of HRR with CA for different injection timings of diesel fuel with OEH gas of 4.6 lpm at rated load

Figure 12. Variation of in-cylinder pressure with CA for different injection timings of diesel fuel with OEH gas of 4.6 lpm at rated load

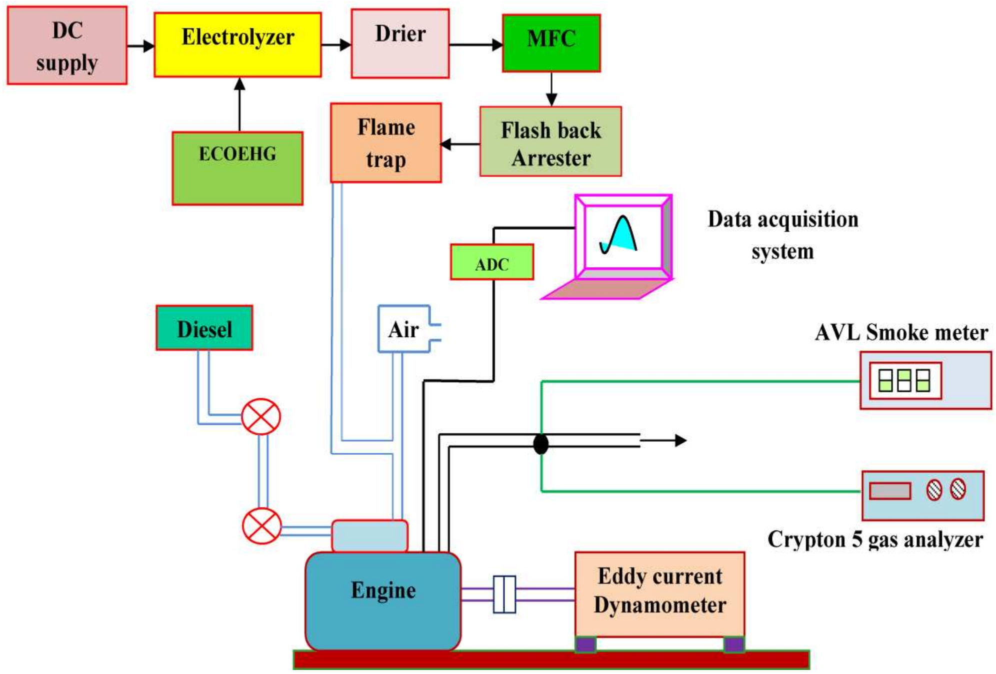

Figure 1. Schematic arrangement of experimental setup

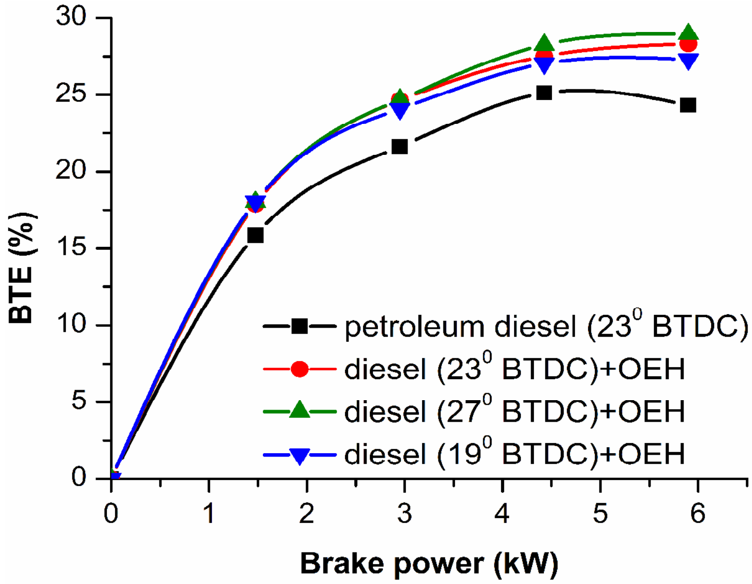

Figure 2. Variation of BTE with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

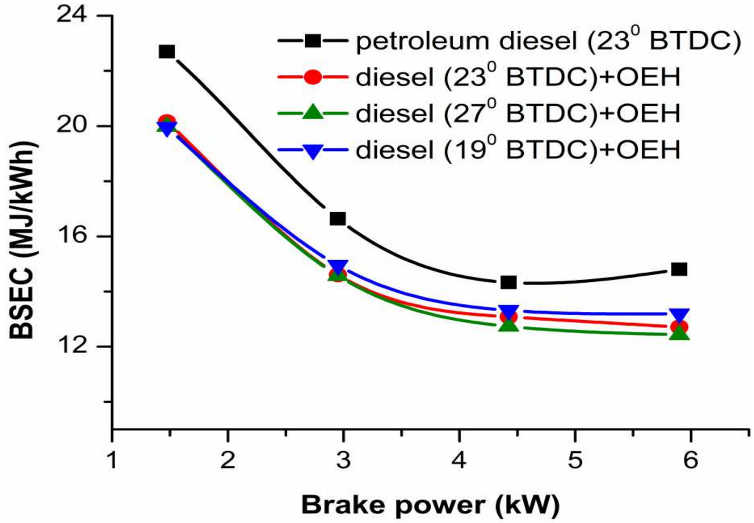

Figure 3. Variation of BSEC with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

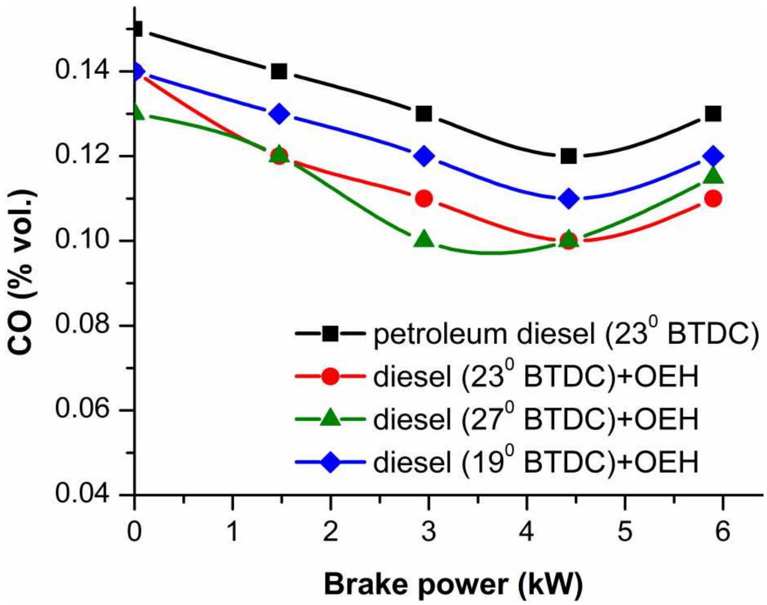

Figure 4. Variation of CO with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

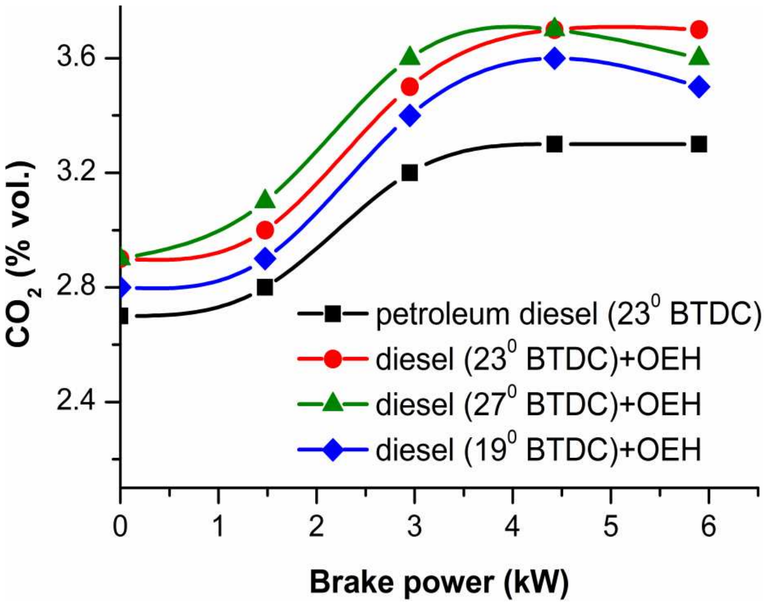

Figure 5. Variation of CO_2 with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

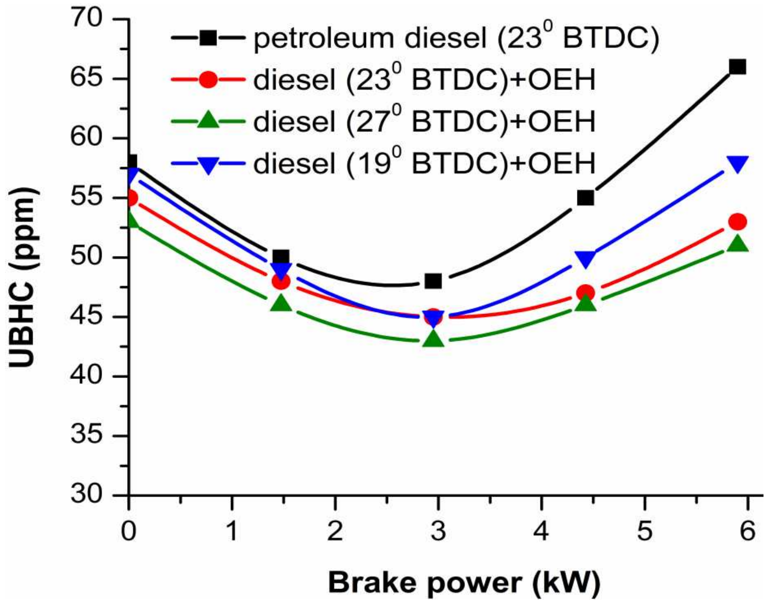

Figure 6. Variation of UBHC with BP for different injection timings of diesel fuel with OEH gas 4.6 lpm

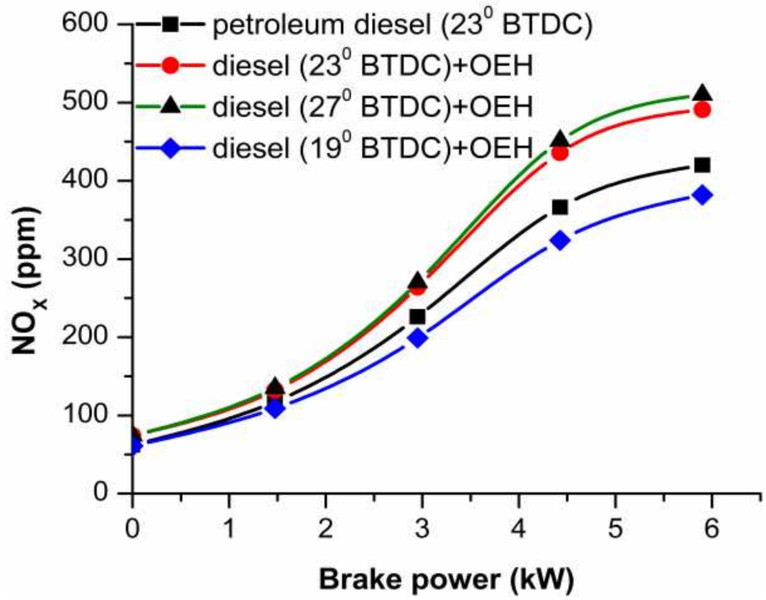

Figure 7. Variation of NO_X with BP for different injection timings of diesel fuel with OEH gas 4.6 lpm

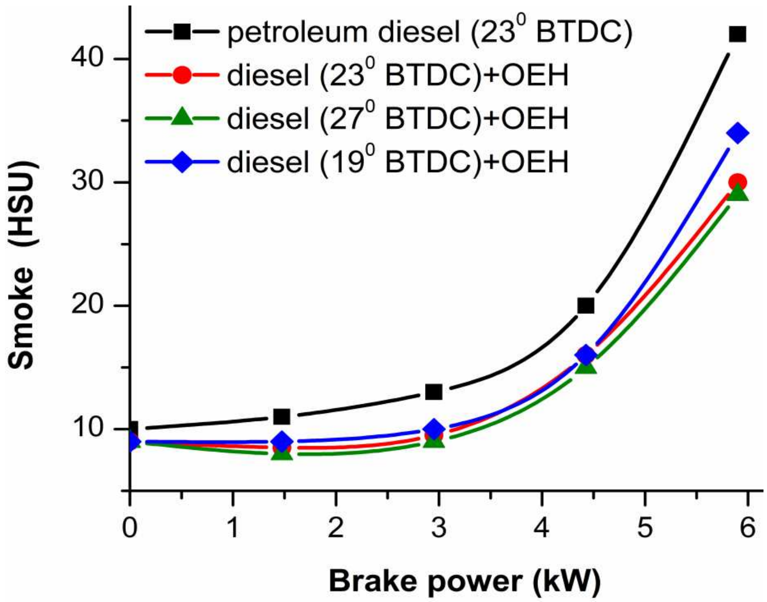

Figure 8. Variation of smoke emission with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

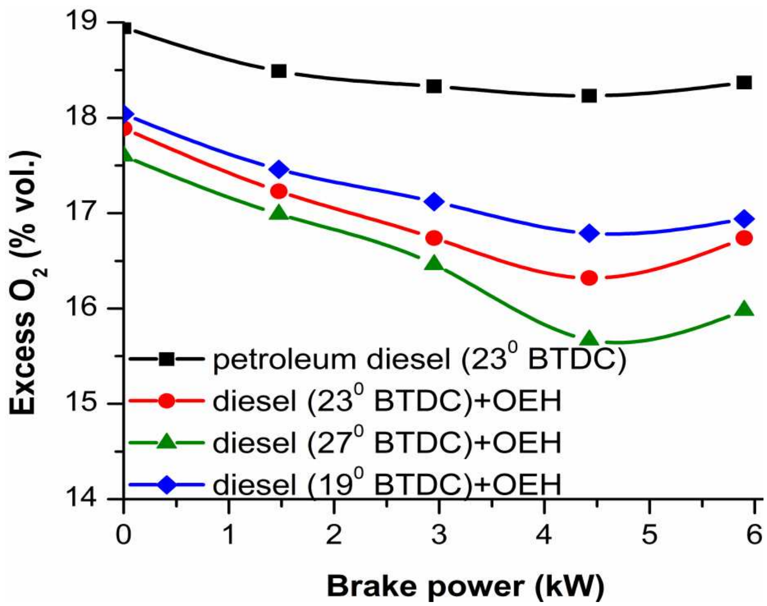

Figure 9. Variation of excess oxygen emission with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

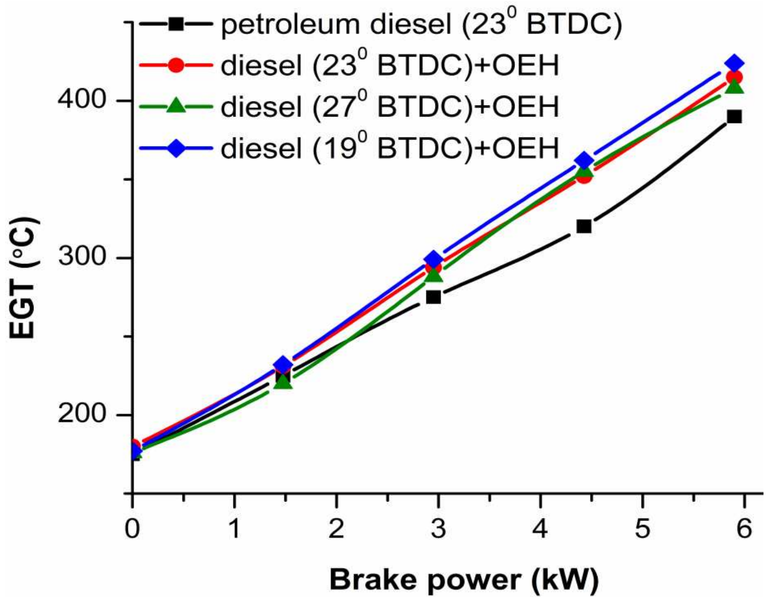

Figure 10. Variation of EGT with BP for different injection timings of diesel fuel with OEH gas of 4.6 lpm

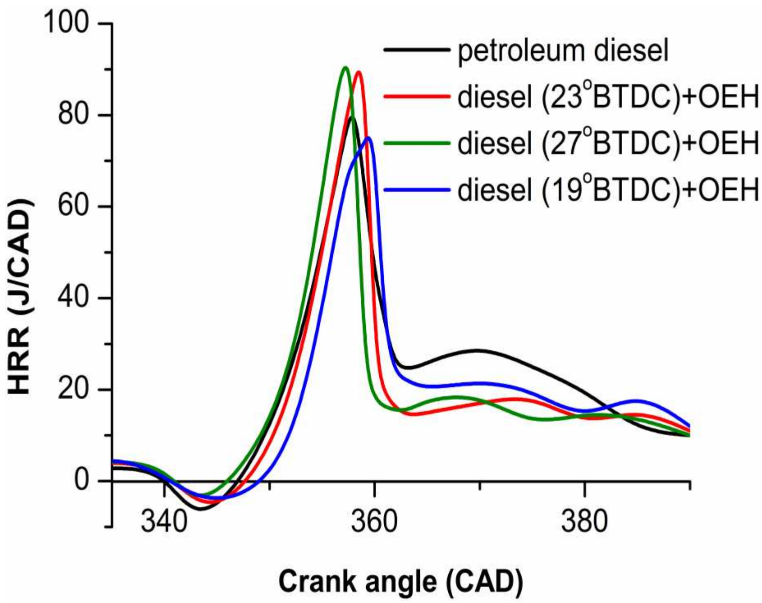

Figure 11. Variation of HRR with CA for different injection timings of diesel fuel with OEH gas of 4.6 lpm at rated load

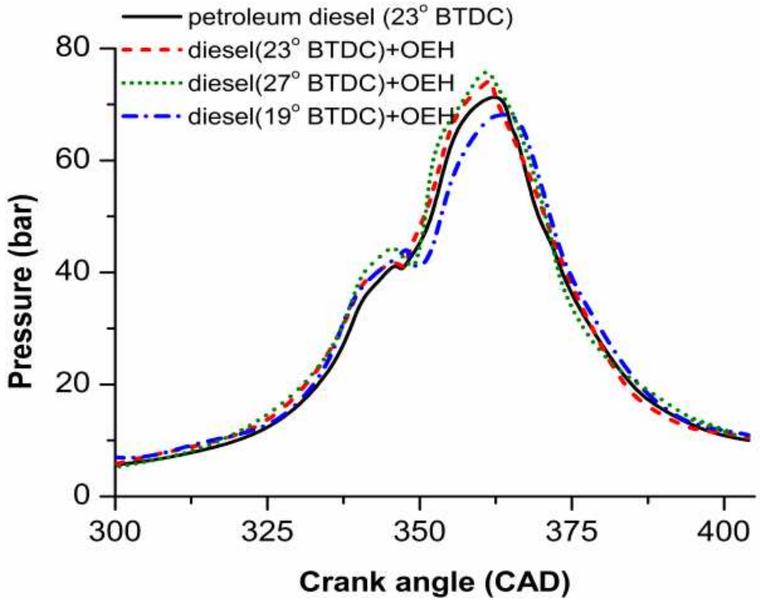

Figure 12. Variation of in-cylinder pressure with CA for different injection timings of diesel fuel with OEH gas of 4.6 lpm at rated load