PERFORMANCE AND EXHAUST EMISSION ANALYSIS OF HHO ENRICHED BIO-DIESOHOL FUEL BLENDS USAGE IN A SINGLE CYLINDER CI ENGINE

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ABSTRACT

Performance and emission analysis of a single cylinder CI engine fuelled with biofuel mixtures, which contain the various combination of biodiesel (5/10/15), diesel (90/80/70), anhydrous ethanol (5/10/15) and hydroxy gas (HHO) to compare with the diesel fuel base condition have been done for the first time in this experimental study. The aim of the study is to reduce fossil fuel dependence and also harmful exhaust emissions gas. Maximum reduction of carbon monoxide and carbon dioxide emission was obtained with 0,5 liter per minute hydroxy gas enriched biodiesel (10%) - diesel (80%) and ethanol (10%) fuel blend. Additionally, unsurpassed brake power and brake torque improvements were provided by same fuel blend, similarly. The results which have been obtained as performance and emissions were very promising except NO_x and BSFC increments compared to sole diesel usage. Furthermore, thermal and volumetric efficiencies are conducted, calculated and presented by graphs.

1. INTRODUCTION

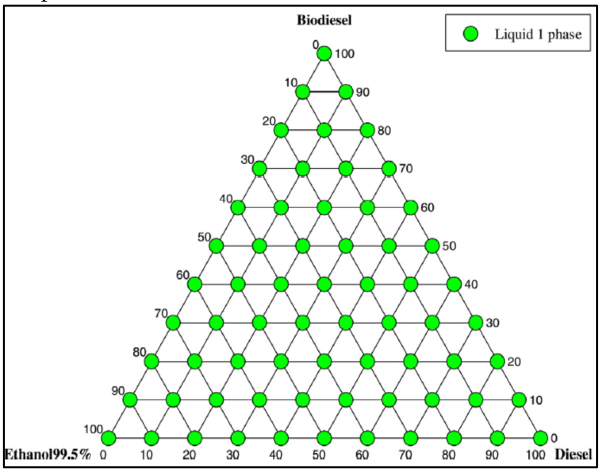
Oil and petroleum products are at the forefront of almost all crises that the world has lived in over the last decades. This crisis is most felt by those who have depended to oil import and the economy which is based largely on oil revenues. Bio-origin fuels can offer a viable solution to the worldwide energy demand crisis. Various biofuel sources such as biomass, biogas, primary alcohol, vegetable oil, biodiesel have been investigating by scientists. These alternative sources are generally environment-friendly, but they need to be assessed for their advantages, disadvantages and specific applications. While some of these fuels are directly available, some must be reformulated to bring them closer to conventional fuels. Researchers have done numerous studies on alternative fuels and also with their combinations. Those which similar to the subject of this study focused on different combinations of diesel, biodiesel, ethanol liquid fuels and hydrogen gas fuel [1-8]. On the other hand, none of the studies in literature contains any combination of diesel + biodiesel + ethanol + HHO at the same time. The aim of this experimental study is to fulfil this gap and take it one more step further.

Although petroleum and petroleum-derived fuel reserves have a decent occupancy rate for many years, the damage of the changing climate conditions due to the rapidly increasing global warming is only possible to reduce by using low carbon or carbon-free fuels. Despite the high initial investment cost, sustainable and renewable energy sources play an important role in solving problems such as climate conditions changing and increasing energy demand. New technologies that must be used to achieve the full of about 150 Petawatt-hours (PWh) of fossil fuels from sustainable and renewable sources of energy require a great deal of investment. it is seen as a better choice to pass by using fuel mixtures, such as fossil fuels, hydrogen, and biofuels instead of a direct transition to alternative energy sources. [9]

Although biodiesel fuel is considered as a good alternative to diesel engines, some biodiesel fuels cannot meet of world standards such as ASME and EN 590 in terms of fuel properties when used alone. These properties can be improved by adding bioethanol. Ethanol affects some important properties related to blending stability, viscosity and

lubricity, energy content and cetane number by mixing with diesel fuel [10].
Firstly, bioethanol, which is considered as an alternative to petrol used in spark-ignition engines, is also suitable for use in compression ignition engines. [11]. Huang et al. performed their experiments with different ethanol addition ratios which are 10%, 20%, 25% and 30% with in ethanol-diesel fuel mixtures. In this study, performance values showed that when ethanol contents of fuel mixtures were increased, brake specific fuel consumption increased but brake thermal efficiency values decreased with same trend [12]. According to many researches, the LHV of ethanol is the major reason of these performance outputs [13-15]. On the other hand, the emission values were improved by using ethanol blended diesel fuel mixtures in their study. Carbon monoxide (CO) were reduced at the mid and high engine speeds. Total hydrocarbon (THC) and nitrogen oxides NO_x values were also improved by ethanol addition in diesel fuel [12]. Di et al. investigated that the various ethanol addition (2%, 4%, 6% and 8%) to ultra-low sulfur diesel fuel usage in direct injection (DI) compression ignition engine. Their investigation was focused on the effects of different ethanol-diesel fuel mixtures on emissions characteristics. Brake thermal efficiency was increased with the increasing ratio of ethanol in the fuel mixture. The CO and total hydro carbon emissions were reduced by using ethanol-diesel fuel mixtures but they observed more NO_x formation with respect to diesel fuel [16]. Rakopoulos et al. also studied with different amount of ethanol (5% and 10%) diesel fuel blends. The results showed that the same characteristics as the given studies previously; as well as the ethanol contents of fuel mixtures were increased; BSFC values increased, BTE values decreased [17]. Shadidi et al. investigated the effects of diesohol fuel blends on the performance and emission characteristics of a tractor engine. The results showed that engine power and torque values were increased 8.50% and 10.28%, respectively. They also observed that emission parameters such as, CO, unburned hydrocarbon (UHC) and CO_2 were improved by using diesohol fuel [18].
It is well known criteria that biodiesels are mixable with alcohols, unlike diesel fuels. Subbaiah and Gopal performed their experiments with ethanol blended rice bran oil (RBO) biodiesel fuel mixtures. They investigated effects of using different ethanol (2.5%, 5% and 7.5%) addition to RBO biodiesel in compressed ignition engine. Their results showed that the 2.5% addition of ethanol improved performance outputs and maximum brake thermal efficiencies was obtained 6.98% and 3.93% higher than standard diesel and biodiesel, respectively [19].
When considering normal conditions, ethanol-diesel fuel mixtures do not remain as a homogeneous mixture for a long time, and biodiesel can be used as a good additive in stabilizing this mixture. A chart is given in figure 1 to explain homogeneity of these three different liquid fuels.

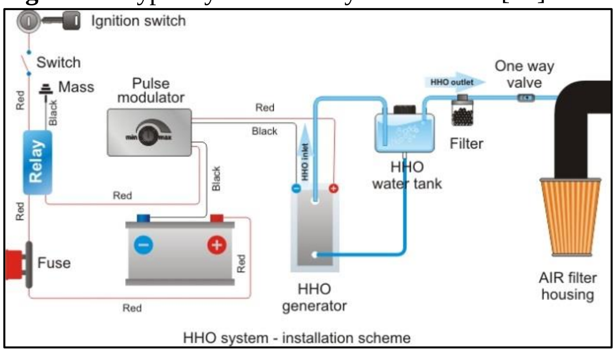
Fig. 1. Diesel–biodiesel–ethanol blends phases at room temperature [20]



Lebeckas et al. conducted their study with ethanol-diesel-biodiesel fuel mixtures. The fuel composition composed of 15% ethanol, 80% diesel and 5% biodiesel. They reported smoother engine operation for all performance parameters with biodiesel addition to ethanol-diesel fuel mixtures according to neat ethanol-diesel mixtures. The experimental results showed that ethanol (15% volume), diesel (80% volume) and biodiesel (5% volume) fuel mix can be used to increase efficiency in performance and emissions parameters of diesel engines [21]. Hulwan and Joshi, performed another study about ethanol-diesel-biodiesel fuel mixtures. During their experiments, they used different amount of ethanol, diesel and biodiesel in mixtures, fuel mixtures contents were D70/E20/B10 (blend A), D50/E30/B20 (blend B) D50/E40/B10 (blend C), and Diesel (D100). The main goal of their investigation was to substitute diesel with maximum amount of ethanol in diesel–ethanol blends by using ethanol-diesel blend stabilization property of biodiesel. The results showed that all performance values were improved except BSFC and all emission values were reduced with all blends except NO_x emissions at mid and high loads [22].

In last two decades, hydrogen plays a key role as an energy source of transportation sector. The many researches have been done about performance and emission effects of hydrogen usage in internal combustion engines [23-28]. In order to use hydrogen as a single fuel in internal combustion engines, both storage safety and engine construction must be considered, although hydrogen can be used as fuel enrichment without any structural changes but it is difficult to overcome the storage problem on-road applications, except HHO systems [29-34]. The applications of HHO systems are made with dry cells. The flat type dry cells are widely used to produce HHO gas from pure water and catalyst mixture, on-road systems. Thanks to its thin structure, flat-type dry cells allow you to add more plates and to use the gaps efficiently during applications [35]. The widespread model usage of this system is presented in figure 2.

Fig. 2. Flat-type dry HHO cell system schema [36]



Also these advantages provide to produce more HHO gas when needed in heavy duty engine applications. Sankar performed his study with different ratios of HHO enriched biodiesel fuel mixtures. The results were reported that performance and emission parameters were improved by using biodiesel with HHO enrichment usage in diesel engine [35]. Many studies in the literature show improvements in the performance and carbon emissions of HHO enriched biodiesel fuel in compression ignition engine [29, 37-39]. Jeffrey and Subramanian used HHO and neem oil ethyl ester in a single cylinder four stroke diesel engine. The performance parameters such as brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC), were calculated and results showed that BTE was increased, BSFC was decreased by using HHO enriched biodiesel when compared with neat diesel operation [40]. Kale and Dahake performed a review study about performance and emission analysis of HHO and biodiesel blends in compression ignition engines. Their results obviously recommended that HHO enriched biodiesel could be used, due to improvement effects of hydrogen enrichment in biodiesel on performance and emission outputs [41].

2. MATERIAL AND METHODS

The pure raw soybean oil has processed and converted into biodiesel by traditional transesterification method which includes chemical reactions, washing, separation of glycerine with pure water, drying, and filtering steps. Liquid test fuel analysis of diesel and biodiesel-diesel-ethanol fuel combinations which were used in this experimental study were performed and shown in table 2. Three different BDE (biodiesehol) fuel mixtures were named by their volumetric composition of the new fuel contents; which are BDE (5/90/5), BDE (10/80/10), BDE (15/70/15). As an example, the mixture BDE (5/90/5) indicates the fuel ratios of the all used substances in the fuel mixture: 5 % biodiesel, 90 % diesel fuel and 5 % ethanol, in terms of volume. By the ratio of ethanol in the fuel mixture increases, the density of the mixture was decreased. The density of ethanol is lower than the other two components of the mixture, causing the density of the fuel mixture to drop. On the other hand, opposite situation is obtained by the ratio of biodiesel in the mixture. Therefore, a balance point has been caught about density.

Additionally, hydroxy gas (HHO) was used with a constant 0.5 liter per minute flow rate to enrich intake air and improve combustion efficiency during the entire tests.

This experimental research was conducted on the single cylinder test engine which powered by diesel-biodiesel-ethanol fuel blends those enriched by 0.5 l/min HHO gas fuel during the entire tests. Schema of the experimental test rig and the test engine which is non-modified, naturally aspirated, one-cylinder stationary engine are shown in figure 3 and table 1, respectively. It is equipped with simple air cooling system with a suitable size fan. All the experiments were performed under full load condition within the range of 1200 to 3200 rpm and graphical points were selected at intervals of 100 rpm. The brake engine torque is determined by means of a hydraulic dynamometer and a measuring unit.

Fig. 3. Experimental Set-up

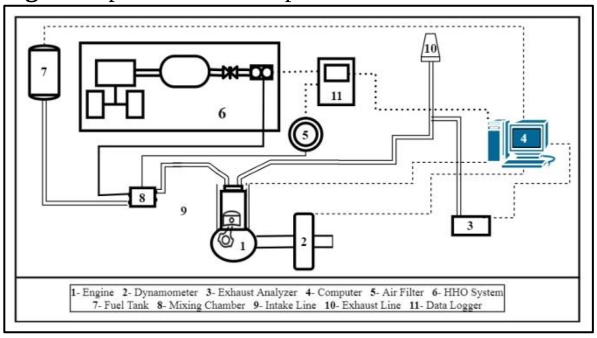


Table 1. Test engine specifications

Type	4 stroke, single cylinder, diesel engine
Displacement	219 cc
Bore & Stroke	70mm * 57mm
Compression Raito	17:1
Brake tork	8.8 Nm @ 2000 rpm
Brake power	3 kW @ 3600 rpm

The HHO gas system contains plate type dry cells with 14 plates, electrolyte added water reservoir, a flash tank, solenoid relay switch, constant current Pulse Width Monitor (PWM) with LCD screen, fittings and electrical connections as represented in figure 4. HHO generator was powered by engine battery (12 V). 10 amps were enough to produce necessary HHO amount. Constant rate of 0,5 L/min HHO flow was controlled with the aid of needle vane before the Alicat brand HHO flowmeter.

Table 2. Test fuel specifications

Specifications	Measurement Device	Diesel	BDE (5/90/5)	BDE (10/80/10)	BDE (15/70/15)	EN590 Standards	EN 14214 Standards
Density (g/cm^3)	Kyoto Electronics DA-130	0,835	0.835	0.835	0.834	0.820-0.845	0.86-0.90
Cetan Number	Zeltex ZX440	55,22	63.383	58.939	59.347	Min. 51	Min. 51
Cetan Index	Zeltex ZX440	45,63	49.918	53.614	56.006	Min. 46	-
LHV (kJ/kg)	IKA Werke C2000	44,280	42,720	42,630	41,160	-	-
Pour Point (°C)	Tanaka MPC-102	-18	- 27.8	- 27.1	- 25.4	-	Sum< 4.0 Win<-1.0
Viscosity (cSt) (40 °C)	Tanaka AKV-202	3,06	2,55	2,1	2,51	2-4.5	3.5 - 5.0

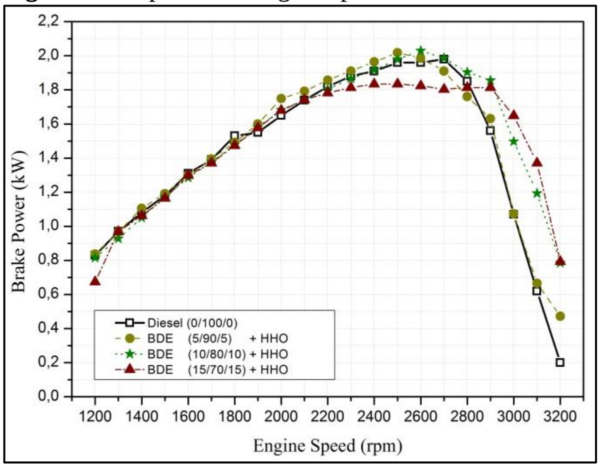
Fig. 4. Experimental HHO system

Exhaust emissions results were obtained by MRU Delta 1600 V gas analyser which has measuring ranges for CO, CO_2 and NO_x emissions 0-10%, 0-20% and 0-4000 ppm, respectively.

3. RESULTS AND DISCUSSION

With the aim of combustion character analysis for the test fuel mixtures which are enriched by HHO gas; the measured and recorded performance and emission values of the diesel test engine have been presented with graphs in this section. Results have been interpreted by comparison each other and also base line diesel properties. Along with different interpretations, the general view is that performance losses are expected when fuel mixtures are used with lower heating values while improvements are expected in exhaust emissions [42-46].

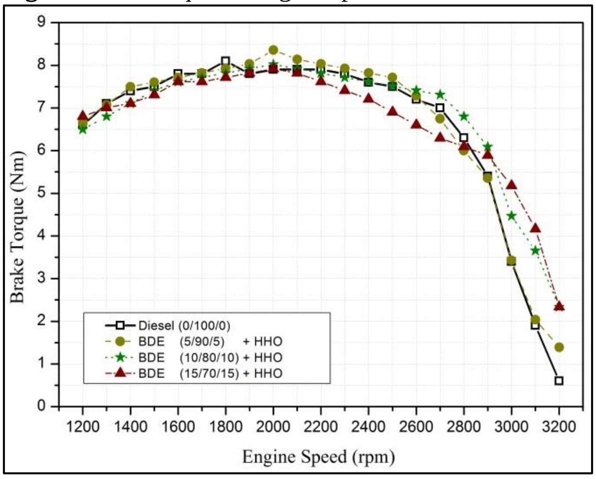
Fig. 5. Brake power vs engine speed



Under these conditions, HHO enrichment is critical in terms of results. The using of hydrogen in internal combustion engines increase the in-cylinder temperature and provide a more efficient combustion phenomenon in terms of thermodynamics. Hydrogen has significant properties compared to the conventional liquid fuels, when used as a fuel or fuel additives thanks to its higher heating value and flame speed. [29].

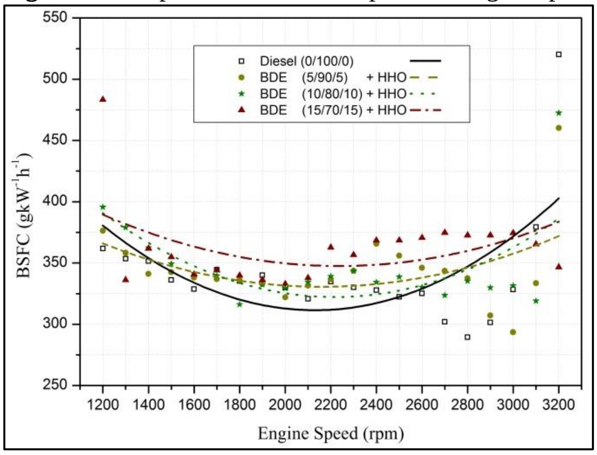
As seen in figure 5, overall brake power vs. engine speed is improved for BDE (5/90/5) + HHO, BDE (10/80/10) + HHO and BDE (15/70/15) + HHO compared to neat diesel fuel (0/100/0). Maximum brake power point is obtained at 2600 rpm by BDE (10/80/10) + HHO. It is clear that HHO affected power outputs positively. Increased volumetric ratio of biodiesel and ethanol in the fuel mixture had a trend to reduce brake power, especially at middle engine speed range (2000-2900 rpm). But when considered about high-speed ranges more than 3000 rpm, HHO enrichment and extra oxygen contents of test fuels provided better combustion. This trend can be observed as long as the effect of the extra oxygen in the fuel for combustion process is greater than the impact of the increased value of the latent heat of vaporization [47]. BDE (10/80/10) + HHO test fuel usage was provided 5.9% improvement compared to neat diesel results. Other mean brake power improvement ratios vs neat diesel fuel were 4.15% and 2.08% for BDE (5/90/5) + HHO and BDE (15/70/15) + HHO, respectively.

Fig. 6. Brake torque vs engine speed



Brake torque results provided similar character as brake power. Constant 0.5 l/min HHO enrichment of BDE (10/80/10) represented highest overall brake torque increments while peak point was obtained by BDE (5/90/5) + HHO as brake torque. Improvement ratios compared to neat diesel fuel were 1,43 %, 3,59 %, 1,35% for HHO enriched BDE (5/90/5), BDE (10/80/10) and BDE (15/70/15), respectively. High engine speeds are more favourable for all HHO enriched experimental test fuels.

Fig. 7. Brake specific fuel consumption vs engine speed



As known, BSFC is the rate of fuel consumption divided by the brake power produced. In other terms, it is a measure of the fuel efficiency to compare the efficiency of internal combustion engine. In this experimental study liquid fuel consumption was measured by the aid of computer, sensors and software. Beside, HHO gas fuel enrichment was provided except neat diesel fuel tests. Amount of hydrogen consumption should be considered to get realistic BSFC results during the calculations. Therefore, pure hydrogen fuel quantity in 0.5 l/min HHO was calculated and transformed to same amount diesel fuel. Since oxygen part of HHO gas cannot be called as fuel, it just enhances combustion, means that it does not contain the calorific value to be considered. Additionally, mass proportion of H:O is 1/8. As a result of these principles, the equivalence of 0.5 liter HHO is 0.085 gr diesel fuel by the point of energy content. The BSFC results of experiments are shown in figure 7. The entire HHO fortified test fuels were increased BSFC by 1 % with compared to base diesel fuel results, which are very acceptable when considered the improvement in brake power and torque outputs. Maximum increment was obtained by BDE (15/70/15) test fuel which might be expected. Because of the highest proportional content of biodiesel (15% v/v) and ethanol (15% v/v) among other test fuel mixtures while it was still the same flow rate of HHO enrichment to combustion room.

Fig. 8. CO vs engine speed

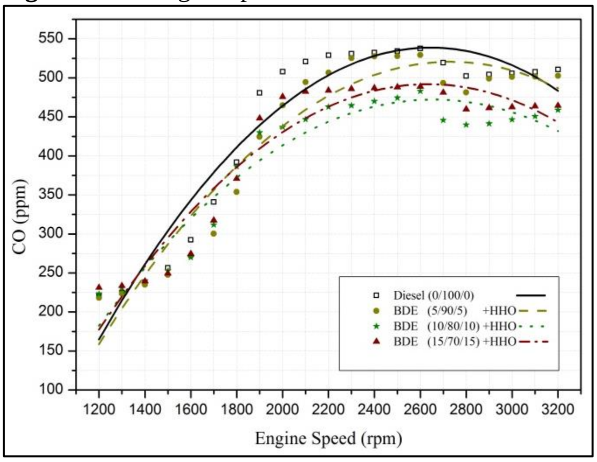
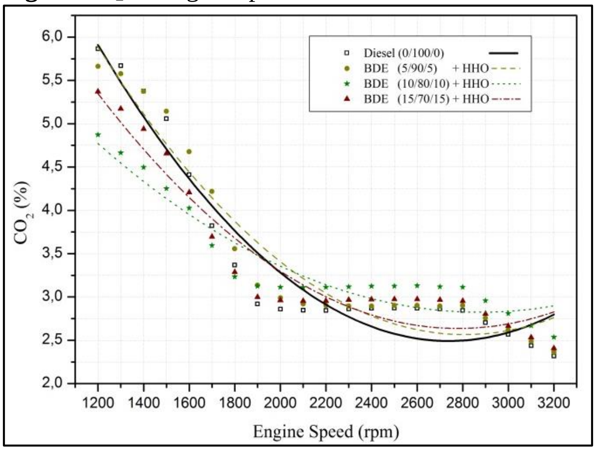
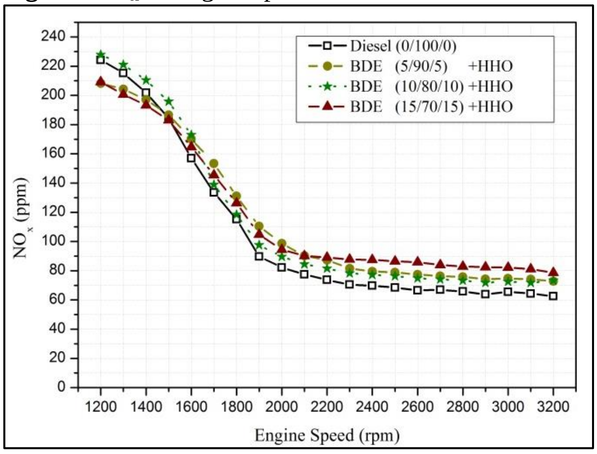


Fig. 9. CO_2 vs engine speed



In figure 8, CO versus Engine speed is shown by graph. As it is seen from the figure, all fuel mixtures were provided better combustion by hydrogen addition and the CO formations were decreased. The best reduction was achieved with BDE (10/80/10) + HHO fuel mixture at a rate of 10% in average, whereas the minimum CO reduction was 4.08% in average with BDE (5/90/5) + HHO fuel mixture. Especially at high engine speeds where the lack of enough time for combustion, the higher flame speed of HHO and ethanol leads better combustion than neat diesel fuel. Therefore, better improvements were occurred at high engine speed range than low and middle ranges. These reductions were obtained by hydrogen enrichments and extra oxygen content of HHO and other alternative fuel mixture. The hydrogen and oxygen content of the HHO contributed to the complete combustion, increasing the formation of CO_2. It is obviously seen from figure 9 that CO_2 formations were lower than base diesel reults at low engine speed for entire HHO enriched alternative fuel combinations. On the other hand, CO_2 formation levels were more than base diesel when the middle and high engine speed ranges were examined. Absence of carbon molecules in HHO and lower C:H proportions for alternative fuels lead a reduction on CO_2 exhaust emissions. The obtained emission values show that hydrogen enrichment reduces emissions of carbon-derived harmful gases, especially when performance improvements are considered. BDE (10/80/10) + HHO and BDE (15/70/15) + HHO experimental fuels provided 1,34% and 1,18% overall reductions, respectively. Additionally, BDE (5/90/5) + HHO was the sole fuel combination among all that increased the average CO_2 emissions compared to base diesel. Overall increment ratio was 2,05%.

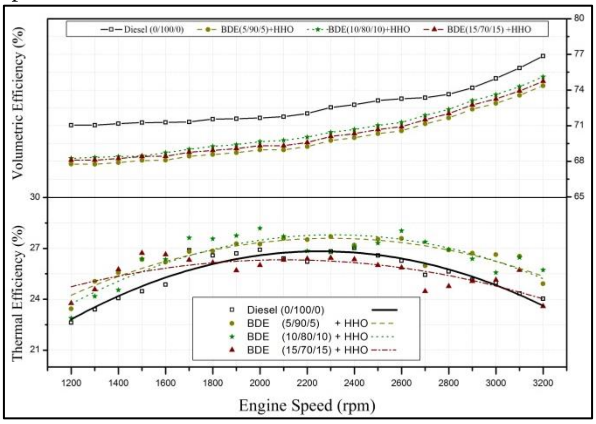
Fig. 10. NO_x vs engine speed



NOx exhaust emission versus engine speed results are represented in figure 10. Three main factors can be listed as the main reasons for NOx exhaust gas emission which are (i) high temperature, (ii) oxygen concentration, and (iii) the residence time [29]. Singular or plural existences of these three main factors increase NOx formation during the combustion. Since hydrogen increases in-cylinder temperature; furthermore provides extra oxygen to the combustion chamber as similar to biodiesel and ethanol fuels which are listed above as the main factor for NOx emissions. As a result, NOx emission is directly related to test fuels and their fuel characteristic. Experimental results showed that 0,5 l/min HHO enriched BDE (5/90/5), BDE (10/80/10) and BDE (15/70/15) were increased NOx emissions 7,65%, 6,74% and 9,15%, respectively.

The volumetric and the thermal efficiencies versus engine speed graph are given by figure 11. The volumetric efficiency is defined as the ratio of the amount of fresh air or fuel-air mixture entering the cylinder on the intake stroke to the amount of fresh air or fuel-air mixture that can be entered in ideal conditions (reference pressure and temperature).

Fig. 11. Thermal and volumetric efficiencies vs engine speed



The major problem with hydrogen and HHO usage as a fuel or fuel additive are that when the hydrogen and HHO in the gas phase are taken into the cylinder, they occupy high volume in the cylinder [33]. Therefore, the volumetric efficiency values are decreased at medium and low engine speeds when compared to neat commercial fuels, thanks to long valve opening time. On the other hand, the brake thermal efficiency graph is given in the same figure. Although the general expectation that the hydrogen usage always increases performance parameters, it is seen from the figure that the brake thermal efficiencies were decreased at low and high engine speed. These decreases may define as the use of hydrogen reduces volumetric efficiency at low engine speeds and reduces combustion efficiency due to high flame speed at high engine speeds.

3. CONCLUSION

Analysis of HHO enriched bio-diesohol on performance and exhaust emission in a single cylinder CI engine analysis have been successfully conducted in this research area as a leading-edge experimental study. Sole diesel fuel results were the reference point in order to make comparison between various blend ratios. This extended experimental research presents:

- analysis and characterization of liquid test fuels (diesel, biodiesel, ethanol) and their different volumetric blends
- replacement of the diesel fuel with environmentally friendly up to 30% without any structural changes or modification on test engine
- experimental investigation of the combustion process (from the view of performance and exhaust emission results)
- determination of most promising and optimum hydroxy gas enriched biodiesehol combination

Very promising results have been obtained as performance and emissions, however, minimum NOx emission and the BSFC increment ratios were 6,7% and 1,05%, respectively. Overall best and optimum coupling between the constant flow rate of 0,5 l/min HHO enrichment with various volumetric ratio mixtures of alternative fuels is determined BDE (10/80/10) + HHO from both views of performance and emission point. BDE (10/80/10) + HHO fuel blend comprises 20% (v/v) renewable and antipollution characteristic fuels with respect to standard diesel fuel.

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