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Impacts of Water Inclusion in Diesel Fuel on Engine Emission Parameters at Various Injection Timings

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Abstract: Today, as a results of diminishing fuel resources and increasing environmental pollution, various biofuels such as biodiesel have been considered as alternatives to their respective fossil-oriented fuels. The present study was focused on assessing the impacts of different water inclusion rates, (i.e., 3, 5 and 7 wt%) into B5 at different injection timings. Emission characteristics of the emulsified fuel blends were analyzed using a single cylinder diesel engine at different engine loads. The findings obtained showed that the lowest level of water included in the emulsion fuels, i.e., 3% and advancing injection timing led to the most favorable HC emission reduction compared with neat B5 and neat diesel. The results of the present study also revealed that by increasing water inclusion rate into B5, NO_x emission could be increasingly reduced. Moreover, retarding injection timing intensified NO_x emission reductions.

Key words: Biodiesel, water additive, emulsified fuel, diesel engine, emission characteristics, injection timing

INTRODUCTION

Developing clean energy resources has noticeably grown due to the limited fossil fuel resources and their adverse impacts on the environment and public health caused. Diesel fuel as one of the most widely used fossil-oriented energy carriers is responsible for a large portion of the Greenhouse Gasses (GHG) emissions (Hassan and Kalam, 2013). On the other hand, the environmental concerns associated with the vast utilization of fossil fuels has led to more stringent regulations on automotive exhaust gas emissions. Amongst renewable resources of energy, biodiesel has significantly attracted a great deal of attention as a green alternative to fossil-diesel. This is ascribed to the fact that biodiesel could be easily blended with fossil-diesel at any percentages and that at inclusion rations below 20% no engine modifications would be required. Furthermore, the combustion of biodiesel-diesel blends result in lower emissions compared with neat diesel fuel (Akbar *et al*., 2009).

It should also be mentioned that biodiesel offers other advantages over diesel fuel such as biodegradability, non-toxicity and higher lubricity (Marchetti *et al*., 2007). Biodiesel could be produced from any types of vegetable oils or animal fats but among the various feedstocks used low quality oils such as Waste Cooking Oil (WCO) are considered promising as they do not led to a fuel vs. food competition. Moreover, biodiesel production from WCO also offers an efficient recycling strategy to simultaneously reduce the cost of biodiesel production and prevent the negative impacts of WCO disposal on the environment.

As mentioned earlier, biodiesel combustion leads to lower emissions of unburned Hydro Carbons (HC), Particulate Matter (PM) and Carbon mon Oxide (CO) while it could result in increased Nitrogen Oxides (NO_x) emission when high biodiesel inclusion rates are used (Puhan *et al*., 2007; Zheng *et al*., 2008). In response to this increase in NO_x emission, engine modifications such as using variable intake valve timing and Exhaust Gas Recirculation (EGR) have been proposed. However, such methods are still not capable of adequately meeting the automobile emission standards pertaining to No_x emission (Hebbar and Bhat, 2013). Therefore, the application of different fuel additives has been put into

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practice during the last decade to achieve further reductions in harmful engine emissions particularly NO_x (Mehta *et al*., 2011; Shaafi *et al*., 2015; Shahir *et al*., 2015).

Among the different types of additives studied, water addition into diesel-biodiesel fuel blends has been found as a promising solution to reduce exhaust gases emissions (Koc and Abdullah, 2013). Water could be included in diesel-biodiesel fuel blends using different strategies, i.e., Water-Diesel Emulsion (WDE), water fumigation and direct water inclusion into the cylinder in order to reduce NO_x-PM trade-off. Among water inclusion strategies mentioned, WDE fuel could reportedly is advantageous as no engine modifications is required while it also triggers an important phenomenon in combustion called micro-explosion (Basha and Anand, 2011; Bertola *et al*., 2003; Hagos *et al*., 2011; Ithnin *et al*., 2014; Kadota and Yamasaki, 2002). In this phenomenon, a secondary atomization of the injected emulsion fuel takes place due to the rapid evaporation of the water initially encapsulated in the injected fuel droplet. This in turn results in an enhanced combustion quality and consequently less emissions could be expected (Hagos *et al*., 2011). In line with that numerous studies have been conducted on the combustion of WDE emulsion fuels to evaluate the engine emissions characteristics (Liang *et al*., 2013; Lif and Holmberg, 2006; Basha and Anand, 2012; Samec *et al*., 2002). For instance, according to Lin and Wang (2004a, b), the output gases temperature, NO_x, CO emissions and smoke opacity were increased during the combustion of ternary and binary WDE emulsion fuels.

Fahd *et al*. (2013) also conducted a study on the effect of 10% water inclusion into diesel fuel on a four cylinder diesel engine and reported lower NO_x emissions but argued that the treatment led to increased CO emission (Fahd *et al*., 2013). Ithnin *et al*. (2015) investigated four different levels of water inclusion (i.e., 5, 10, 15 and 20%) into diesel fuel (WDE fuels) and found simultaneous NO_x and PM emissions decreases while increases in CO and CO_2 were observed in response to all the water levels tested. In another study, Abdullah and Koc (2011) conducted a study on the addition 10% water into different biodiesel-diesel blends and they observed NO_x emission reduction while CO emission increased.

Water inclusion could also result in varied fuel properties such as fuel viscosity and such variations play an important role in determining ideal combustion conditions. In fact, exhausted emissions of a given fuel blend is influenced by the combustion conditions, e.g., Start of Injection (SOI), injection pressure, etc. For instance (Armas *et al*., 2005) argued that higher viscosity values of fuel blends could result in advanced injection timing. Nevertheless, to the best of our knowledge, little has been done to determine the impacts of combustion conditions on the engine emissions caused by water inclusion in different biodiesel/diesel blends.

Accordingly, the current study was aimed at surveying emission behavior of three different WDEs, i.e., B5 containing low-levels of water, (i.e., 3, 5 and 7%) at different engine SOI, (i.e., 35, 38 and 41°) on a Ricardo E6 single cylinder diesel engine. The findings of the present study could be of interest since by finding the most favorable fuel injection timing, minimum engine emissions could be achieved.

MATERIALS AND METHODS

Biodiesel production: Biodiesel was made from acid pre-treated WCO using methanol and in the presence of an alkali catalyst (potassium hydroxide) in a stirred batch reactor at 60°C for 1 h as reported in our previous report. IThe water consumed during the washing process of the produced biodiesel was minimized by following the technique explained by Jaber *et al*. (2015). In addition, some of the obtained biodiesel properties derived using "Biodiesel Analyzer© Ver. 2.2" Software (available on "http://www.brteam.ir/biodieselanalyzer") was used (Talebi *et al*., 2014).

Fuel samples preparation: Water were emulsified in 1 L of B5 at three levels, (i.e., 3, 5, 7 % wt.) (B5W3, B5W5 and B5W7, respectively). To obtain a stabilized emulsion, 75 ml of a surfactant (including 1:1 wt. tween 80 and span 80) (Merk, Germany) was added into B5 prior to the addition of water and was homogenized for 10 min in an ultrasonicator bath (Model LBS 2 Labsonic Ultrasound bath) at room temperature. Subsequently, engine emissions tests were conducted at different loads and by using the different B5-water emulsions, neat B5 and neat diesel fuels.

Engine set-up: The experiments were run on a single cylinder, natural aspiration, four-stroke and direct injection diesel engine (Ricardo E6). The engine specifications are shown in Table 1 and the schematic diagram of the engine test setup is shown in Fig. 1. HC, CO_2 and CO emissions were analyzed using an SPTC gas analyzer (infrared) while O_2 and NO_x emissions were measured by using an electrochemical method. Emission

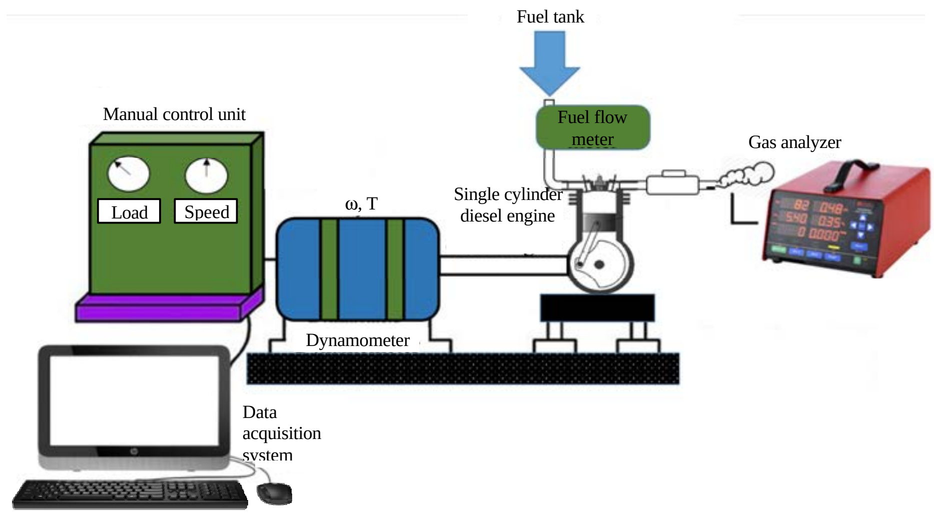

Fig. 1: The experimental engine setup

Table 1: Specifications of the engine test bed and dynamometer used in the present study

Single cylinder, four-stroke diesel engine, natural aspired	
Models	Ricardo
Brand	E6
Bore	105 mm
Stroke	120 mm
Displacement	0.507 L
Compression ratio	17:1
Connecting rod length	192 mm
Intake Valve Closing (IVC)	18°BTDC
Intake Valve Opening (IVO)	37°ABDC
Exhaust Valve Opening (EVO)	56°ABDC
Exhaust Valve Closing (EVC)	11°ATDC

Table 2: Specifications of the gas analyzer used.

Parameters	Range	Resolution
HC	0-20,000 ppm	1 ppm
CO	0-10%	0.01 vol
CO_2	0-20%	0.1 vol%
O_2	0-4% by vol.	0.01 vol%
	4-22 vol%	0.1 vol%
NO_x	0-4000 ppm	1 ppm

tests were carried out at a constant engine speed and four different loads (i.e., 25, 50, 75 and 100). The gas analyzer pipe was exposed to the exhaust gas in the exhaust gas outlet of the engine and the data were recorded. The measurement accuracy of the gas analyzer is presented in Table 2.

RESULTS AND DISCUSSION

Fuel properties: Table 3 present the fatty acid profile of the WCO used and the physicochemical properties of WCO biodiesel produced, respectively. Accordingly, the properties of the produced biodiesel were in line with the specifications of the American Society for Testing and Materials (ASTM) standards, i.e., ASTM D6751. Water inclusion into the B5 fuel was found to result in reduced

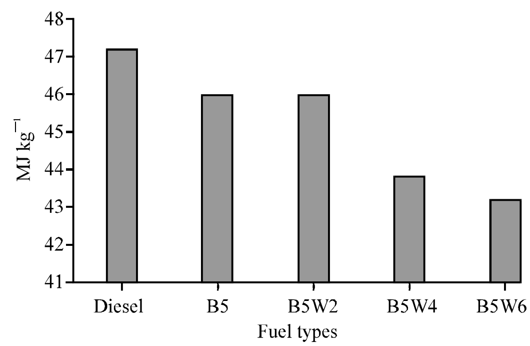

Fig. 2: Calorific value of the tested fuel blends

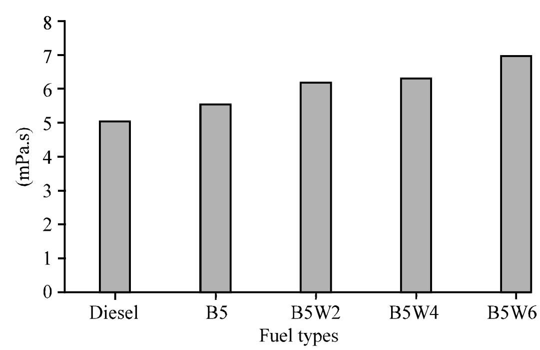

Fig. 3: Viscosity value of the tested fuel blends

Table 3: Fatty acid profile of the WCO used

Fatty acid composition	(%)
Myristic (C14:0)	0.71
Palmitate (C16:0)	33.18
Stearate (C18:0)	4.69
Oleic (C18:1)	41.02
Linoleic (C18:2)	18.09
Linolenic (C18:3)	1.03

heating values of all fuel blends while it led to increased viscosity values (Fig. 2 and 3). These findings were in agreement with the those of Ithnin *et al.* (2015). Incrased viscosity could be attributed to the efficient dispersion of the water particles in fuel by ultrasonication processing leading to increased friction and static electricity attraction among the fuel particles (Lin and Chen, 2006).

Emission characteristics: The obtained measured emissions of NO_x, HC, CO, CO_2 and O_2 at different loads and SOIs of the engine are presented in Fig. 4-8.

CO emission: Incomplete combustion of fuels is considered by many as the main factor leading to CO generation (Lee *et al.*, 2011). More specifically, there are two main reasons behind CO emission increasing) high air/fuel ratios resulting in decreased cylinder temperature during combustion) lack of sufficient amounts of oxygen to oxidize CO at high loads and high fuel/air ratios. In the present study, the addition of biodiesel into diesel fuel decreased CO emission especially at 100% load probably due to the oxygen content of biodiesel resulting in an improved combustion.

Increases in CO emission were observed in response to water addition into B5 (Fig. 7) and the changes were proportional to the amount of water

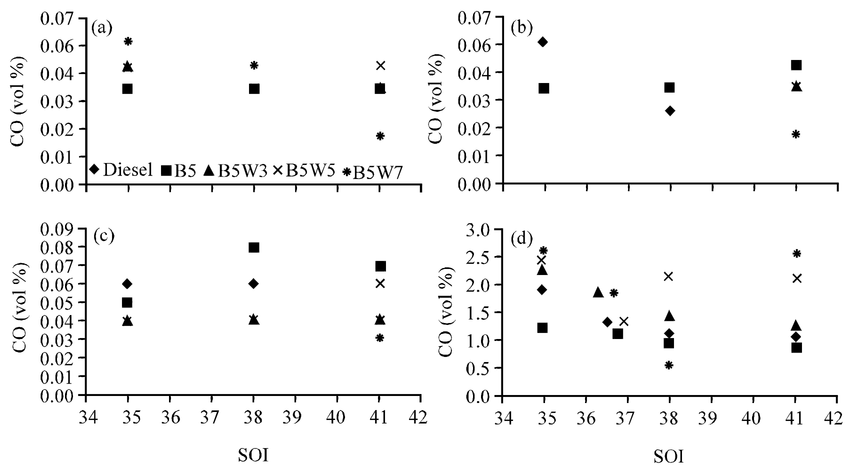

Fig. 4: Variations observed in CO emissions for the different fuel blends at different SOI: a) 25% load; b) 50% load; c) 75% load; d) 100% load

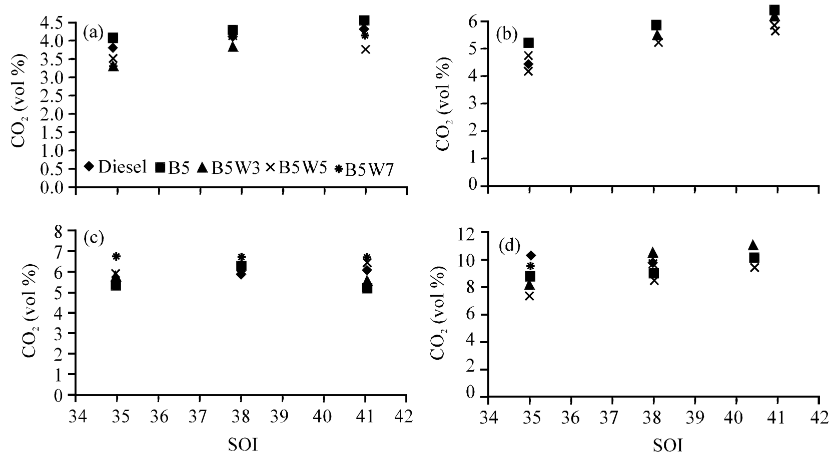

Fig. 5: Variations observed in CO_2 emissions for the different fuel blends at different SOI: a) 25% load; b) 50% load; c) 75% load; d) 100% load

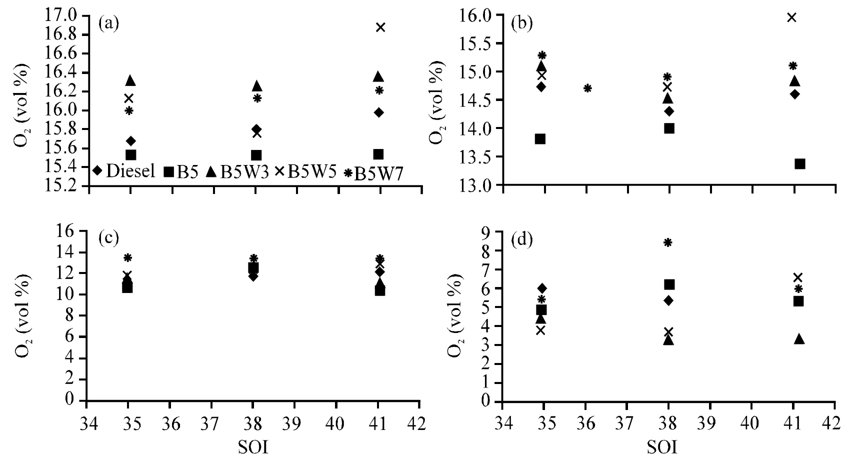

Fig. 6: Variations observed in O_2 emissions for the different fuel blends at different SOI: a) 25% load; b) 50% load; c) 75% load; d) 100% load

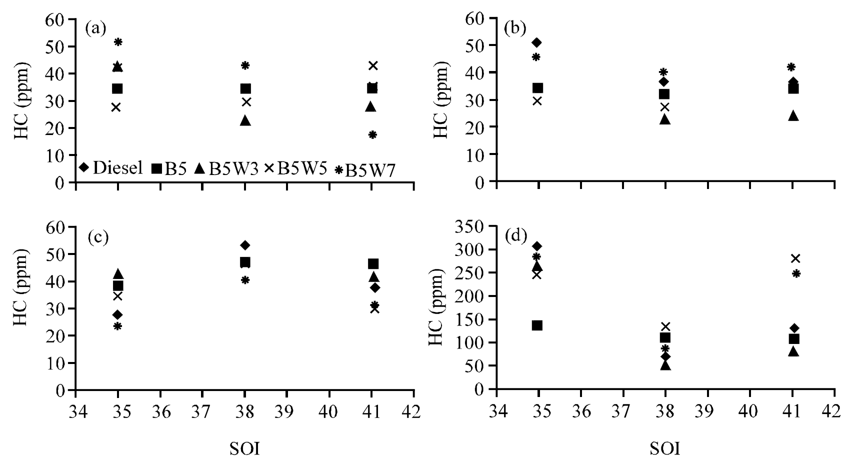

Fig. 7: Variations observed in HC emissions for the different fuel blends at different SOI: a) 25% load; b) 50% load; c) 75% load; d) 100% load

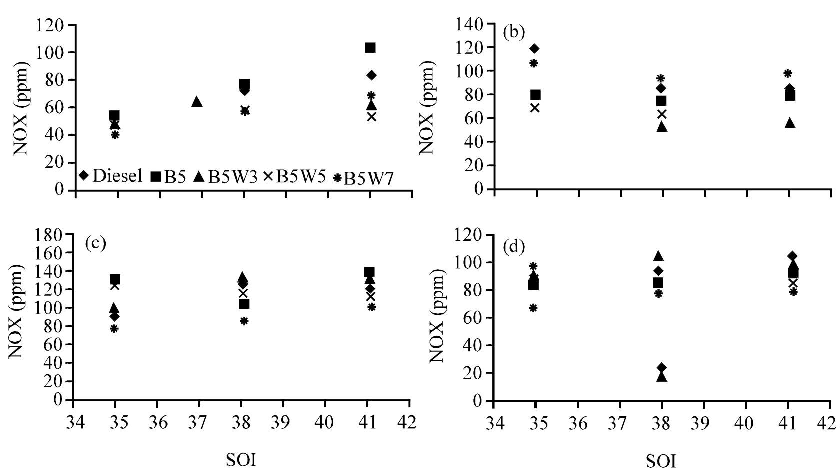

Fig. 8: Variations observed in NO_x emissions for the different fuel blends at different SOI: a) 25% load; b) 50% load; c) 75% load; d) 100% load

Table 4: Measured and estimated physicochemical properties of WCO biodiesel

Fuel property	Values	Methodology
Kinematic viscosity (cSt)	100°C/40°C 0.96/6.1	ASTM D445
Flash point (°C)	168	ASTM D92
Fire point	184	ASTM D92
Cloud point (°C)	6	ASTM D2500
Density (20 °C)	0.875	ASTM D1296
SFA (Saturated fatty acid)	39.52	Biodiesel analyzer©
PUFA (Polyunsaturated fatty acids)	19.12	Biodiesel analyzer©
DU (Degree of saturation)	79.50	Biodiesel analyzer©
SV (Saponification value)	201.00	Biodiesel analyzer©
IV (Iodine value)	72.92	Biodiesel analyzer©

included. Increasing especially at 100% load. The lowest CO emission was achieved when the B5W7 fuel blend was combusted. This could be ascribed to the effect of the micro-explosion phenomenon and the consequent more efficient mixing of the injected fuel and air (Kumar *et al*., 2006). Similar results have been reported by Abdullah and Koc (2011) and Davis *et al*. (2012) who also investigated water inclusion into biodiesel/diesel blends (Abdullah and Koc, 2011; Davis *et al*., 2012). In a different investigation, Debnath *et al*. (2013a) also claimed that the emulsion produced by adding 5% water into biodiesel-diesel diminished CO emission by 67%. They attributed the CO reduction achieved to the oxygen content and lower carbon/hydrogen ratio of biodiesel in comparison with neat diesel (Debnath *et al*., 2013a, b) (Table 4).

Variations in SOI showed that advancing SOI compared with standard injection led to decreased CO emission in case of neat diesel and B5. Similarly, inclusion of water into the fuel blends resulted in reductions in CO emission at higher SOIs. Overall and if considering all the fuel blends investigated, the best combustion was achieved at 41° of SOI. Nevertheless, minimum CO emission at 100% load took place at the standard SOI of 38° for the B5W7 fuel blend, 46 and 51% reduction in CO emission compared with B5 and neat diesel, respectively.

CO_2 emission: The CO_2 emission of all fuel blends are presented in Fig. 5. Based on the findings of the present study, the combustion of B5 resulted in a slight reduction in CO_2 emission at standard SOI compared with neat diesel. These observations could be attributed to the fact that in comparison with diesel fuel, biodiesel has a lower carbon/hydrogen ratio which could consequently cause less CO_2 emission (Labeckas and Slavinskas, 2006). However, retarding or advancing the injection timing led to further CO_2 emission when B5 was used compared with neat diesel. This could be explained by the higher oxygen content of biodiesel (Mofijur *et al*., 2016; Nwafor, 2004). On the contrary, this trend was not observed in case of water-emulsified B5 fuel blends. More specifically, the inclusion of water in general led to reduced CO_2 emission compared with neat B5 and neat diesel at all the SOIs tested especially when B5W7 was combusted. This could be ascribed to the cooling effect of water during combustion leading to less oxidization of hydrocarbon into CO_2 (Ithnin *et al*., 2015).

Overall, the most favorable result was obtained at the standard injection timing. More specifically, CO_2 emission increased when the B5W3 was used at 100% load probably as a result of the positive impact of micro-explosion on better combustion of the fuel blend and consequently higher amount of CO_2 was observed (Al-Sabagh *et al*., 2012).

O_2 gas: The result of oxygen emission is presented in Fig. 6. The amount of oxygen measured when a fuel is combusted is indicative of the leanness or richness of the fuel/air ratio. A rich fuel/air ratio will logically reduce the amount of O_2 in the exhaust gases. It should also be mentioned that at a constant air/fuel ratio, incomplete combustion could cause and extra oxygen content in the exhaust gases. Indeed, it indicates that the oxygen could not to be employed in order to improve the combustion quality. As shown in Fig. 6, water inclusion in B5 led to a higher amount of emitted O_2 compared with B5 and neat diesel. Nevertheless, this result could not be attributed to the lower combustion quality of water-emulsified B5 fuel blends becausea significant portions, (i.e., 3, 5 and 7%) of the emulsion fuels were contributed by water and this in turn led to higher amounts of oxygen in the exhausted gases. In fact, the presence of water in B5 increased the combustion quality and this could be obviously verified at 100% load where 3 and 5% water inclusion caused lower emitted O_2 compared with B5 and neat diesel. Standard injection timing (38°) in almost all types of fuel blends resulted in more complete combustion but at 100% load, the minimum O_2 emission was achieved at 41° when B5W3 was used.

HC emission: One of the properties which is an indication of incomplete combustion is the amount of HC emission. The observations made in the present study revealed that the B5 combustion led to slightly increased HC emission at high engine loads compared with neat diesel fuel. This could probably be due to the effect of surfactant in increasing fuel viscosity.

At all engine loads, addition of 3 and 5% water into B5 led to notable reductions in HC emission compared with both B5 and neat diesel as mentioned earlier as a result of micro-explosion (Fig. 7) while B5W7 increased HC emission compared with B5 and neat diesel. Apprantly, the positive impacts of micro-explosion phenomenon could not compensate for the excessive cooling of the combustion chamber at elevated water level of 7% (Armas *et al*., 2005). Such justification is in line with the results of the CO_2 emission presented earlier in Fig. 5. In addition, Alkhulaifi and Hamdalla (2011) also argued that water inclusion decreased cetane number which could directly influence the combustion quality. Such increased HC emissions were also reported by Jazair *et al*. (2011) who investigated the combustion characteristics of biodiesel containing 10, 20 and 30% water.

The results of the present study also showed that advanced injection timing reduced HC emission in case of B5 compared with neat diesel. Similar outputs were obtained by water inclusion into B5 for all water ratios compared with neat diesel.

NO_x emission: The most interesting objective of water inclusion into biodiesel-diesel blends is to diminish No_x emissions. Indeed, water can efficiently reduce the high temperature of the flame considered as the main parameter negatively influencing No_x emission (Alahmer *et al*., 2010; Ghojel *et al*., 2006; Glaude *et al*., 2010; Jazair *et al*., 2011). The finding of the current study showed that NO_x emission was reduced using B5 compared with neat diesel at standard injection timing which was in line with the findings of the previous investigators (Davis *et al*., 2012; Debnath *et al*., 2013b; Koc and Abdullah, 2013).

In comparison with the standard injection timing, advancing and retarding the injection timing led to an increase and decrease on NO_x emission in case of all fuel blends. In case of 3% water inclusion, NO_x emission was decreased compared with neat diesel and B5 at low loads while opposite results were observed at high loads. By increasing the amount of water, the reductions achieved in NO_x emissions were further intensified. Therefore, the most favorable NO_x emission reduction was obtained when B5W7 was combusted at high loads and at retarding injection timing of 35° compared with B5 and neat diesel. This finding could be explained by the fact that water inclusion into B5 must have increased the ignition delay due to water resistance against the flame spread and consequently led to NO_x emission reductions (Maiboom and Tauzia, 2011).

CONCLUSION

An experimental study was carried out on a single cylinder natural aspirate diesel engine to investigate the impacts of three levels of water (3, 5 and 7% wt) inclusion into biodiesel-diesel (B5) at different SOIs on exhausted emissions. Inclusion of water into B5 decreased the energy content and increased the kinematic viscosity of the emulsion fuel. The findings of the present study revealed that 7% water inclusion in biodiesel/diesel fuel blend resulted in the lowest CO and CO_2 emissions and that the reductions were minimal at 41° SOI. On the contrary, HC emission was best reduced at lower water levels and by advancing the injection timing, i.e., in case of B5W3 at 41°. Retarding injection timing also reduced NO_x emission while the lowest amount of NO_x emission was achieved by increasing the amount of water included into B5 (i.e., B5W7). These improvements could be ascribed to the occurrence of the micro-explosion phenomenon in response to the water inclusion into the biodiesel/diesel fuel blend.

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