Renewable Energy 37 (2012) 333–344

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Water injection effects on the performance and emission characteristics of a CI engine operating with biodiesel

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ARTICLE INFO

Article history:
Received 5 November 2010
Accepted 21 June 2011
Available online 23 July 2011

Keywords:
Bio-diesel
Engine performance
Emission
Water injection

ABSTRACT

Biodiesel is one of the most promising renewable, alternative and environmentally friendly biofuels that can be used in diesel engine without any need for any modification in the engine. However, researchers have reported that the engines running with biodiesel emit NO_x in higher concentrations. To address this problem, in the present study an experimental investigation has been carried out on the combustion, performance and emission characteristics of a compression ignition (CI) engine running with biodiesel under steady state conditions with a novel NO_x reducing mechanism involving a water injections system. The experimental work has been conducted on a four-cylinder, four-stroke, direct injection (DI) as well as turbocharged diesel engine. In this investigation, biodiesel (produced from the rapeseed oil by trans-esterification process) has been used. During the experiments the in-cylinder pressure, specific fuel consumption, water injection flow rate, fuel flow rate and exhaust emission (NO_x, CO, CO_2 and THC) were measured. The experimental results clearly indicate that water injection at a rate of 3 kg/h results in the reduction of NO_x emission by about 50% without causing any significant change in the specific fuel consumption. Furthermore, the water injection in the intake manifold has little effect on the in-cylinder pressure and heat release rate of the CI engine under different operating conditions.

1. Introduction

Current and future emission regulations are becoming more stringent and the transport sector is undergoing rapid transformation because of these regulations. In addition, the fossil fuel demand is continuously increasing world over resulting in rapid depletion of fossil fuel deposits [1]. These problems are compelling the world to focus on developing/finding alternative fuels to the existing fossil fuels [2]. The major alternative fuels that are being used for the automotive transport are ethanol, hydrogen and biodiesel. Ethanol technology has been successfully established and commercialized in both developing and developed countries. However, ethanol has a limitation of being used only in spark ignition engines. The use of ethanol is also limited to maximum blend strength of 85% only as higher blend strength results in problems in fuel injection system [3]. Hydrogen based fuel cells can become a viable alternative to fossil fuels. However, to make hydrogen use commercially viable, there are many technical challenges that need to be addressed for example complexity in hydrogen production, requirement of special infrastructure for its storage, and high fuel cell production costs. Inspite of research advances on, hydrogen powered fuel cells, and diesel engines are expected to remain in use for high-power applications such as rail road locomotives, ships and over land transport trucks [4]. For these applications the biodiesel fuel appears to be a viable alternative to fossil fuel as its properties match favourably with fossil fuel and there are only few technical challenges that need to be overcome when used in compression-ignition diesel engines [4]. Biodiesel is one of the renewable energy sources, which consists of short chain (methyl or ethyl) esters, produced from vegetable-based oils by transesterification. A large number of studies have shown that biodiesel is one of the most promising renewable, alternative and environmentally friendly biofuels that can be used in diesel engine with little or no modifications in the engine [5–9]. It has also been shown that biodiesel has significant potential to reduce CO_2, CO, THC and PM emissions [10,11].

Even though biodiesel provides engine performance comparable to engine performance with diesel, a considerable number of researchers have reported that the engines running with biodiesel emit higher NO_x concentrations in exhaust [12–14]. NO_x and PM emissions are the major toxic emissions that are being regulated

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doi:10.1016/j.renene.2011.06.035

with emission regulations becoming more and more stringent [15]. This is shown pictorially in Fig. 1[16]. This regulatory requirement has resulted in major research and development works being undertaken to reduce NO_x emissions. Different methods have been used to reduce the NO_x emission successfully from compression-ignition engine; some of these are exhaust gas recirculation (EGR), catalytic converter (post-combustion method) and water injections/emulsion [4]. The working principles and the advantages and disadvantages of these methods are summarised below.

1.1. Exhaust gas recirculation (EGR)

The main principle employed in EGR is recirculation of a portion of an engine's exhaust gas back to the engine cylinders. The recirculated exhaust gas decreases the local temperature in the combustion chamber. It is mostly effective in particular time/space zones during which the NO_x emission is produced, specifically during the fuel injection and after the end of the injections [18]. In the EGR system, the heat of combustion from the fuel is used to heat the exhaust gas. The exhaust gas is essentially inert and therefore does not react in the combustion chamber and only absorbs heat [4]. Even though, the EGR has a potential of reducing NO_x up to 50%, it has an inherent drawback of increasing the PM emissions [2,19,20]. In addition, the heat absorption by exhaust inert gas in the cylinder chamber results in small amount of power loss from the engine as well.

1.2. Post-composition control method

The other method to reduce NO_x emissions is using post-composition control of the exhaust gas to remove the NO_x emission. One such method being used for SI engines for reducing the NO_x emissions is three-way catalytic converter. The catalytic-converter changes NO_x to N_2, CO to CO_2 and unburned hydrocarbons (HC) into H_2O and CO_2.

However, the materials used in catalytic converters include platinum, palladium, and rhodium, which are expensive. In addition, the catalytic converters work best at a stoichiometric air-fuel ratio about 14.1:1. Most of the diesel engines tend to run lean which makes the catalytic converter less effective in reducing NO_x emission [4]. Running lean also produces more over all NO_x emission because of the increase in engine temperature. The other catalytic method of NO_x reduction is selective catalytic reduction (SCR). This method is used for many years in stationery combustion installations to reduce NO_x by injecting ammonia in the presence of catalyst. In the vehicles applications instead of ammonia an aqueous solution of urea (NH_2CONH_3) is used. The SCR can result in NO_x reduction of up to 90% [21]. However, the application of SCR finds most application in heavy vehicle application and has rarely been used in passenger cars. This is because exhaust gas temperature in diesel car is low which makes SCR less effective. In addition, the urea/ammonia management is quite costly and requires modification of the exhaust system for catalyst space and provisions for new urea/ammonia infrastructure and maintenance of the system [22].

1.3. Water injection/emulsion

The third available method to reduce local combustion temperature and consequently the NO_x emission is the injection of emulsion of water into an engine system [23–27]. One of the advantages of the water injection as compared with the EGR and the catalytic converter is the enhanced possibility of reduction of NO_x over the entire engine load range without affecting the PM emission negatively [2]. Even though water is inert, in the combustion cylinder it decreases the local adiabatic flame temperature by absorbing heat of water vapour [28–30]. As a result the NO_x emission, which depends on the peak flame temperature, is reduced [15,31], In addition to the reduction of NO_x, water emulsion reduces the HC, soot and particulate matter as well. There are three main methods that are used to introduce water into a diesel engine. These are direct water injection into the cylinder using separate injector, injecting water/diesel emulsion and spraying/injecting water into the intake manifold [32,33].

The first water based injection system involves direct injection of water within the combustion cylinder. This method provides an option of controlling water and fuel ratio [34]. Southwest Research Institute and Delphi Diesel Systems have developed a real time water injection system for application to heavy-duty diesel engines. The system is integrated with electronic control unit and controls the pump that delivers metered volumes of water to an electronic injector forming diesel and water mixture at the injector tip. It has been reported that this method enables NO_x emission to be reduced by 42% and in combination with EGR this method enables NO_x emission to be reduced up to 82% [35]. The drawback of this method is the amount of complexity involved in integrating additional components to the existing engine system and further requirements of a redesign of the fuel supply system integrated with the engine.

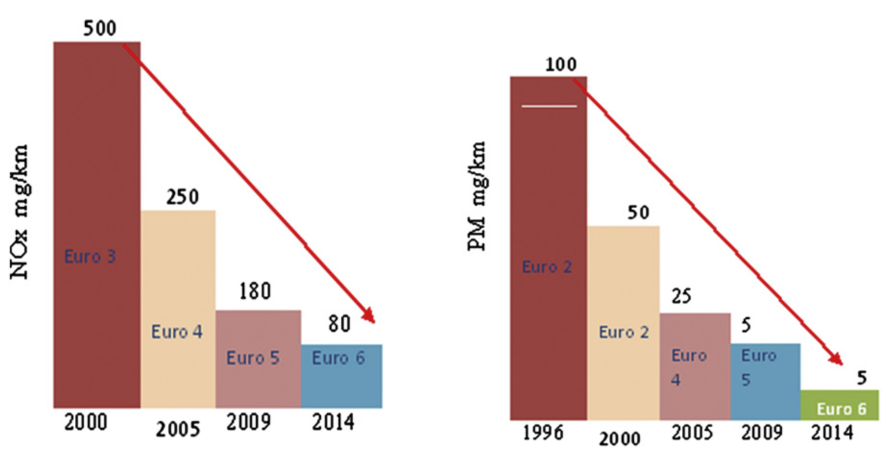

Fig. 1. Passengers cars NO_x emission overview of past and future requirements [17].

The second water based injection system involves emulsification of water and fuel in the presence of some surfactants in an appropriate mixer. It has been also shown that adding water in the fuel may help to improve atomization and mixing characteristics, which is attributed to droplet micro-explosions. The micro-explosions phenomena are induced by volatility differences between the water and the fuel [33]. The water-fuel emulsion methods have several shortcomings that impede emulsion fuels from becoming widely used in the practice. The effects of water emulsion on the performance of the engine vary with the operational modes of the engine. In most of the previous studies the water emulsion has been shown to have positive effect on engine performance parameters [31,36]. The water diesel emulsion has some drawbacks: firstly, the water emulsions needs a more advanced and well developed infrastructure for the implementation of a complex on-board water-in-diesel emulsion production system integrated with the engine, which may increase the cost of the engine [2]. To produce smaller and well scattered water droplets, the engine operating parameters need to be controlled with very high accuracy [33]. Secondly, the physical properties of the fuel emulsion may (viscosity, density and bulk modules) change. It is observed that the viscosity and density of the water emulsified fuel have higher values than the normal fuel [37]. Change in these parameters can significantly affect the performance of the fuel injection system.

The third method of water based injection system is intake manifold water injection. Currently this method is widely used on large marine diesel engines. The water can be injected either downstream of the compressor or upstream of the compressor [23–27,34]. Tauzia et al. [2] had investigated the effects of water injection into the intake manifold of an HDDI Diesel engine. They reported NO_x reduction of up to 50% at an injection rate between 60 and 65% of water over a wide load range. The main advantage of water injection into the intake manifold is its simplicity and ease with which it can be integrated within existing engines and also with any new design. Since in this system water is injected through a separate valve and it does not mix with fuel directly, it does not affect the fuel flow properties in fuel supply line. It can be seen from the above discussion that injection of water into the intake manifolds has potential to be the most effective method of NO_x reduction.

As described above the application of water injection to an engine running with diesel to reduce NO_x emission has been reported extensively. However, little attention has been paid to understand and investigate the effects of water injection on the engine performance and emission running with biodiesel and biodiesel blends. The main objective of the present work is to investigate performance and emission characteristics of a CI engine running with biodiesel and integrated with water injection system into the intake manifold. Furthermore the thermodynamic effects of water injection on the combustion behaviour within the cylinder have also been investigated.

2. Experimental facilities and test procedure

In this study the combustion, performance and emission characteristics of a CI engine, running with biodiesel, without and with water injection have been investigated. The engine used in the present investigation is a four-cylinder, four-stroke, turbocharged, water-cooled and direct-injection CI engine (Fig. 2). Full details of parameters of the engine are included in Table 1. The load to the engine was provided by a 200 kW AC Dynamometer with 4-Quadrant regenerative drive with motoring and absorbing capability for both steady and transient conditions. It is integrated with

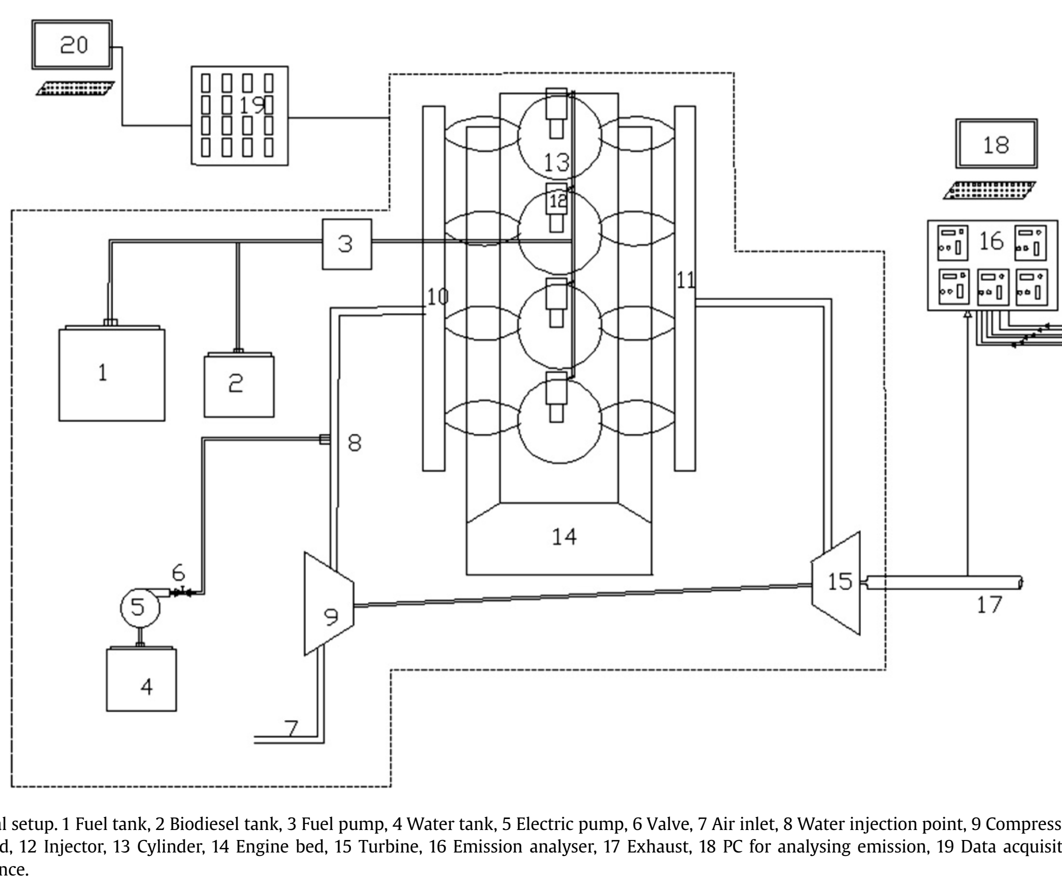

Fig. 2. Experimental setup. 1 Fuel tank, 2 Biodiesel tank, 3 Fuel pump, 4 Water tank, 5 Electric pump, 6 Valve, 7 Air inlet, 8 Water injection point, 9 Compressor, 10 Intake manifold, 11 Exhaust manifold, 12 Injector, 13 Cylinder, 14 Engine bed, 15 Turbine, 16 Emission analyser, 17 Exhaust, 18 PC for analysing emission, 19 Data acquisition system, 20 PC for analysing performance.

Table 1
Characteristics of engine.

Engine type	Turbocharged diesel engine
Number of cylinders	4
Bore	103 mm
Stroke	132 mm
Compressor inlet diameter	60 mm
Compressor outlet diameter	60 mm
Compression ratio	18.3
Number of valves	16
Injection system	Direct injection
Displacement	4.399 L
Cooling system	Water
Recommended speed	850 rpm
Maximum power	74.2 Kw @ 2200 rpm

speed sensors, pressure transducers, thermocouples, air flow metres, fuel flow metres and in-line torque meter. A Hengler RS58 speed sensor was used to measure the speed of the engine. The air-consumption was measured using hot-film air-mass meter HFM5 and the fuel consumption was measured by FMS-1000 gravimetric fuel measuring which was controlled and monitored by CADETV12 software. The cylinder pressure was measured using Kistler 6125A11 model air-cooled piezo-quartz pressure sensor which was mounted on the cylinder head. The cylinder pressure signal was passed through Bruel & KJaer 2635 charge amplifier. The crankshaft position was obtained using a crank angle sensor to determine the cylinder pressure as a function of the crank angle.

All the signals collected from the test rig needed to be converted from an original analogue form to a digital form. This was achieved by using a Cambridge Electric Design (CED) Power 1401 Analogue to Digital Converter (ADC) interface between the transducers and the computer. The Analogue to Digital Converter (ADC) has 16 channels, 500 MHz bandwidth. The fuel from biodiesel tank was pumped to a fuel meter and, then it was passed through a fuel pump to the fuel injectors. The water injection was carried out by using an electric pump attached to a water source. The water was injected downstream of the compressor attached to the intake manifold. The water flow rate was measured by gravimetric method.

The measurement of the gaseous emissions was carried out using a gas test bench HORIBA, Horriba EXSA - 1500. The type of gas analyser and measuring range used in this study are described in Table 2. The sample line of the equipment is connected directly to the exhaust pipe and it is heated to maintain a wall temperature of around 191 °C and avoid condensation of hydrocarbons. The insulted line is extended from the exhaust pipe to the equipment unit where the analysers are located. Both NO_x emission and CO emission analysers are set in one bench. However, each emission analyser uses different principles to measure the emission. Oxides of nitrogen are measured on a dry basis, by means of a heated chemiluminescent detector (HCLD) with a NO_2/NO converter. The carbon monoxide was measured using a non-dispersive infrared (NDIR) absorption type analyser, whereas a paramagnetic detector was employed for the measurement of O_2 concentration in the exhaust flow.

During the testing process the engine was initially run for 10 min to bring it to a steady state before any measurements were carried out. On the day prior to the actual test day and also in between each type of water flow rate tests, a preconditioning procedure was implement that up to 50% by running the engine at a high load and then a low load to purge out any of the remaining effects from previous tests in the engine fuel system and also to remove the deposited hydrocarbon from the sample line. The frequency of the data acquisition system was 37 kHz. The sampling time used was 40 s. The operating conditions are listed on Table 3. The operating conditions were selected with an aim to cover main engine operating speeds and loads as per the New European Driving Cycle (NEDC).

Table 2
The emission analyser type and measuring range.

Emission type	Emission analyser type	Measuring range
CO	Non-dispersive infrared (NDIR)	0–2000 ppm
NO_x	Heated chemiluminescent detector (HCLD)	0–5000 ppm
O_2	Paramagnetic detector	0–25%

Table 3
Operating conditions.

Condition	Speed (rpm)	Load (Nm)	Water flow rate
A	900–1800	105	Without, 1.8 kg/h, 3 kg/h
B	900–1800	210	Without, 1.8 kg/h, 3 kg/h
C	900–1800	315	Without, 1.8 kg/h, 3 kg/h
D	900–1600	420	Without, 1.8 kg/h, 3 kg/h

The biodiesel used in this study was rapeseed oil biodiesel purchased from a local biodiesel producer. The biodiesel was produced by transesterification process from 'virgin' oil using methanol. The main physical properties such as composition, density, lower heating value and viscosity of the biodiesel were measured in the applied science laboratory according to the official test standards and are shown in Table 4.

3. Estimation of experimental work and heat release rate

Heat release rate (HRR) is an important parameter to analyse the combustion phenomena in the engine cylinder. The important combustion parameters such as combustion duration and intensity can be easily estimated from the heat release rate variation over an engine cycle. The HRR diagram provides key input parameters in the prediction models for the NO_x emission. The heat release rate is modelled by applying the first law of thermodynamics as follows:

$$\frac{dQ}{d\theta} = p\cdot\frac{\gamma}{\gamma-1}V\frac{dp}{d\theta}+\frac{1}{\gamma-1}V\frac{dP}{d\theta} \quad (1)$$

$$V(\theta) = \frac{Vd}{\gamma-1}+\frac{Vd}{2\left[R+1-\cos(\theta)-\left(R^2-\sin(\theta)\right)^{\frac{1}{2}}\right]} \quad (2)$$

Where, $dQ/d\theta$ is rate of heat release (kJ/deg), P is the in-cylinder gas pressure, V is in-cylinder volume γ is the ratio of specific heats, V_d is the engine displacement, and R is the ratio of connecting rod length (l) to crank radius (a).

In the Equation (1), the cylinder content is assumed to be a homogeneous mixture of air and combustion products. It is

Table 4
The properties of biodiesel.

Property	Units	Measured
Composition, %	% C	77
	% H	12
	% O	11
Density,	Kg m^{-3}	879
LHV*, KJ/Kg	MJ Kg^{-1}	38.5
Kinematic Viscosity,	mm^2 s^{-1}	4.9

LHV*: lower heating value.

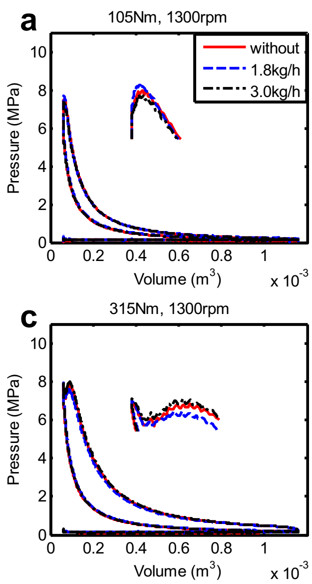

Fig. 3. P–V diagram of CI engine at 1300 rpm and various engine loads.

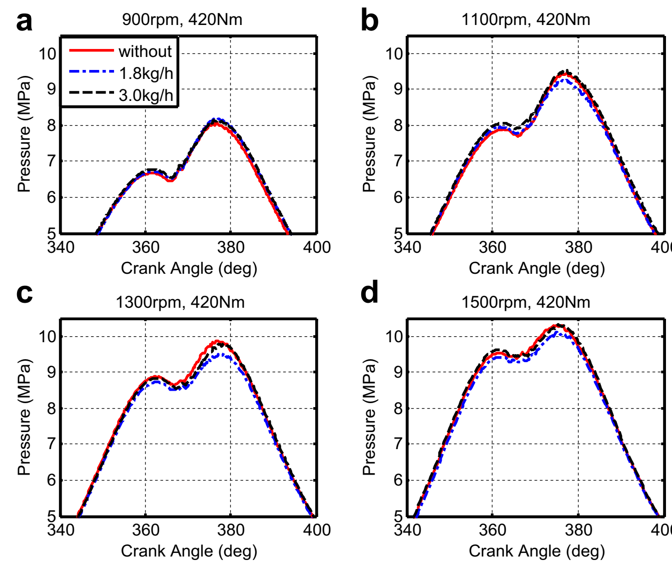

Fig. 5. Cylinder pressure at 420 Nm and at different engine speeds.

further assumed that a uniform temperature and pressure exists at any moment during the combustion process. To determine the HRR within the internal combustion engine by Equation (1), the engine geometry specification as described in Table 1 and cylinder pressure values that were recorded during the tests were used.

Furthermore, the cumulative heat release (Q_{cum}) in the combustion cylinder is found by Equation (2).

$$Qcum = \int dQ = \int P\frac{\gamma}{\gamma - 1}VdP \tag{3}$$

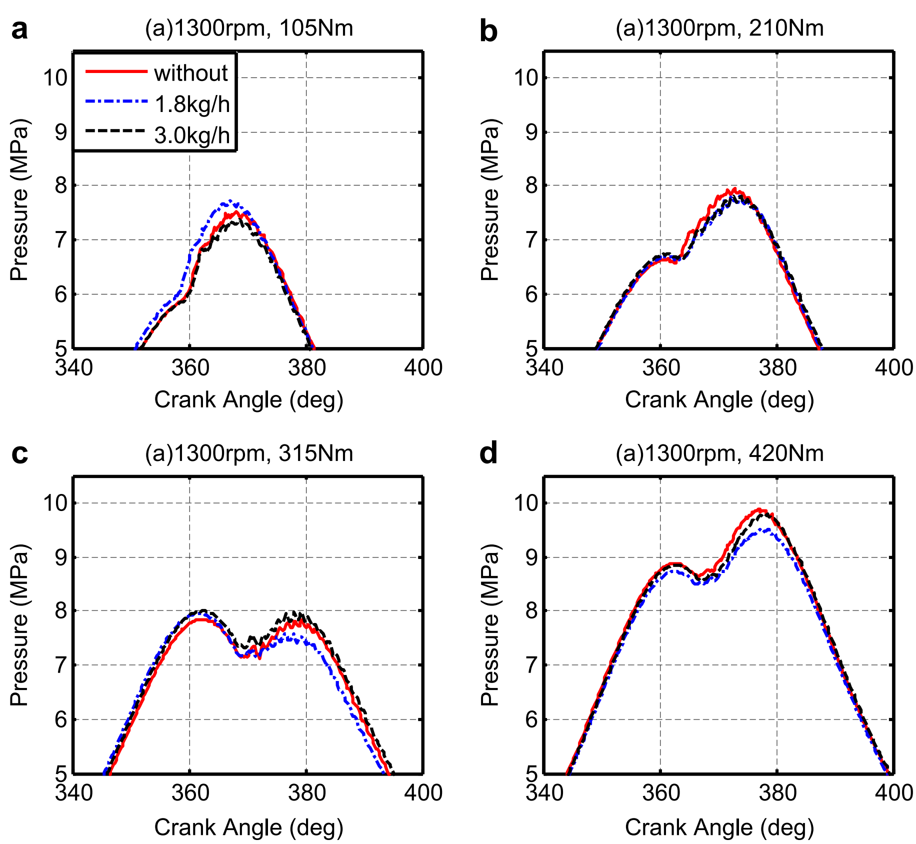

Fig. 4. Cylinder pressure at 1300 rpm and at different loads.

4. Discussion and results

The main scope of the present study is to investigate the effects of water injection into the intake manifold of a compression-ignition engine running with biodiesel on the performance characteristics of the engine. In the following results are presented for all test cases examined with special emphasis on the combustion characteristics, engine performance and exhaust emission.

4.1. Water injection Effects on cylinder pressure and heat release rate

Fig. 3 shows the variation of in-cylinder pressure with cylinder volume for an engine speed of 1300 rpm and at loads of 105 Nm, 210 Nm, 315 Nm and 420 Nm corresponding to different water injection rates (0 kg/h, 1.8 kg/h and 3 kg/h) into the intake manifold. The results show that the P–V diagrams are fairly similar and follow typical characteristics under different operating conditions. Effect of water only shows marginal effect on peak pressure values within the cylinder.

This means the work done by the engine, which is calculated from the P–V diagrams, is not affected greatly by the water injection. The work done calculations show less than 2% change in work output because of water injection.

Figs. 4 and 5 show the variation of in-cylinder pressure with crank angle under different operating conditions for the engine running with biodiesel at different water injection rates (0 kg/h, 1.8 kg/h, 3 kg/h) for engine speeds of 900 rpm, 1100 rpm, 1300 rpm and 1500 rpm at different engine loads of 105 Nm, 210 Nm, 315 Nm and 420 Nm. In both the figures it can be seen that the peak cylinder pressures only have minor differences in magnitude for different water flow rates at a given operating condition.

However, it can be seen that with the change of operating condition, the pressure variation profile changes substantially. This result indicates that the water injection into the intake manifold does not affect the peak flame temperature considerably during the combustion at a given operating condition (speed and load). Instead, the water injection affects the pre-mixed combustion flame temperature at which high concentrations of Nitrogen and Oxygen react to form oxides of Nitrogen [38].

Fig. 6 demonstrates the rate of heat release (ROHR) for the CI engine used in present investigation running with biodiesel with water injection at speeds of 900 rpm and 1300 rpm and at two different loads of 210 Nm and 420 Nm. At lower engine speeds since the vaporised fuel has accumulated during ignition delay [38], at the beginning negative heat release rates have been observed on Fig. 6(a) and (b). However, at higher engine speed (1300 rpm) the heat release rate start with positive ROHR due to the higher fuel-air mixing phenomena (Fig. 6(c) and (b)). In Fig. 6 it can be also seen that the pre-mixed combustion heat release rate of combustion with water injection is higher than the neat fuel. This is because the ignition delay and accumulation of fuel in the combustion chamber at the time of combustion result in higher ROHR [2]. Furthermore, it can be seen from the figures, that the main effect of the water injection on the combustion is to increase the ignition delay. This observation is an agreement with the previous researchers [2,39]. The ignition delay, which is the time (or crank angle) interval between the start of injection and the start of combustion, increases with increasing the water injection flow rate. The ignition delay is because of the cooling effect of water on the inlet air temperature. In addition, addition of water may also have significant effect on the chemical kinetics within the combustion chamber.

At higher loads (as it can be seen in Fig. 6(b) and (d)), the combustion is almost purely diffusive and the influence of water injection on ROHR is less. Since the diffusive combustion rate is governed by the amount of air entrained by the fuel spray per unit of time. In this case with water injected with the air, the spray entrains a water–air mixture instead of pure air, so that an increase in combustion duration is expected.

The cumulative heat release is an important parameter to characterise the efficiency of the combustion process. The cumulative heat release rate is shown in the Fig. 7. The figure shows that at lower engine speeds engine running with water injection has slightly higher cumulative heat release rate than the engine running without water injection. At higher loads the water injection does not show any significant change in cumulative heat release rate.

4.2. Effects of water injection on engine performance

The main engine performance parameters measured in the present investigation are power, specific fuel consumption and thermal efficiency. Fig. 8 shows the variation of the brake specific fuel consumption (bsfc) with speed for different water injection conditions (without water, with 1.8 kg/h water, and 3 kg/h water) at different loads. The bsfc is estimated from the brake power output of the engine and the mass flow rate of the fuel. It can be seen from the figure that the bsfc decreases as the engine speed increases, reaches its minimum and then increases at high engine speeds. This can be explained on the basis that at low speeds, the heat loss through the combustion chamber walls is proportionally greater and the combustion efficiency is poorer. These result in higher fuel consumption for the same amount of power produced. At higher speeds, the power required to overcome friction increases at a higher rate, resulting in a slower increase in output power with a consequent increase in bsfc [31,40]. The percentage change in bsfc because of water injection is depicted in Fig. 9. It can be seen that at lower engine loads (105 Nm and 210 Nm) the bsfc is minimum for engine operating without water injection and water injection at 1.8 kg/h. At higher loads (315 Nm and 420 Nm) the injection of water does not show any significant change in bsfc.

The effects of water injection on the thermal efficiency of engine running with biodiesel with and without water injection have been shown in Fig. 10. The brake thermal efficiency is calculated from of bsfc and lower heating value of the fuel as shown in Equation (4).

$$\eta = \frac{3600}{sfc \times LHV} \times 100 \tag{4}$$

Where η is the thermal efficiency (%), sfc is brake specific fuel consumption (g/kWh) of the biodiesel and *lhv* is lower heating value (kJ/kg) of the biodiesel.

It can be observed from Figs. 10 and 11 that at all the operating conditions the thermal efficiency increases at lower engine speeds, reaches its maximum point and then decreases. At lower loads, the engine brake thermal efficiency corresponding to 3 kg/h water injection decreases by an amount of 3% as compared to the thermal brake efficiency of the engine running without water. At higher loads (210 Nm and 420 Nm) the thermal efficiency of engine running with water injection is slightly higher as compared to no-water injection condition.

4.3. Effects of water injection on NO_x and CO emission

The effects of water injection on exhaust emissions from a CI engine running with biodiesel have been investigated experimentally. Fig. 12 shows the NO_x emission from the CI engine running on 100% biodiesel at loads of 105 Nm and 315 Nm over various engine speeds and at different water injection rates (0 kg/h, 1.8 kg/h, 3 kg/h). At all the operating conditions, the NO_x emissions were found to decrease with the increase in the engine speeds. This can

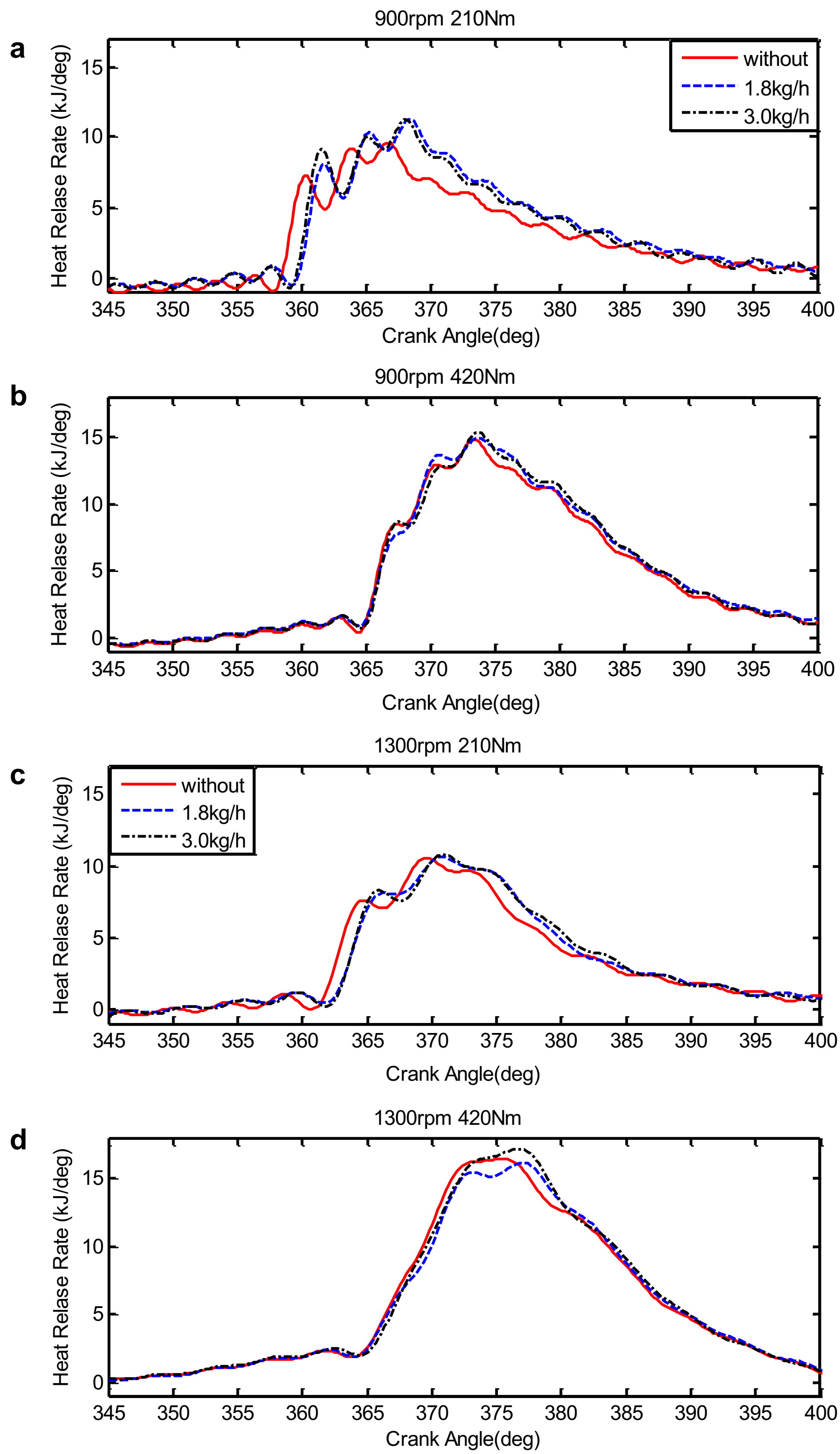

Fig. 6. Heat releases rate at 1300 rpm and different loads.

be explained on the basis that at higher engine speeds the volumetric efficiency and gas flow motion within the combustion cylinders are found to increase and this in turn leads to a faster mixing between air and fuel which results in the minimization of the ignition delay [14]. The reduction of ignition delay minimizes the reaction time of the free nitrogen and oxygen gas in the combustion cylinder which is the main mechanism of NO_x formation. Fig. 12(a and c) clearly depict that when the water

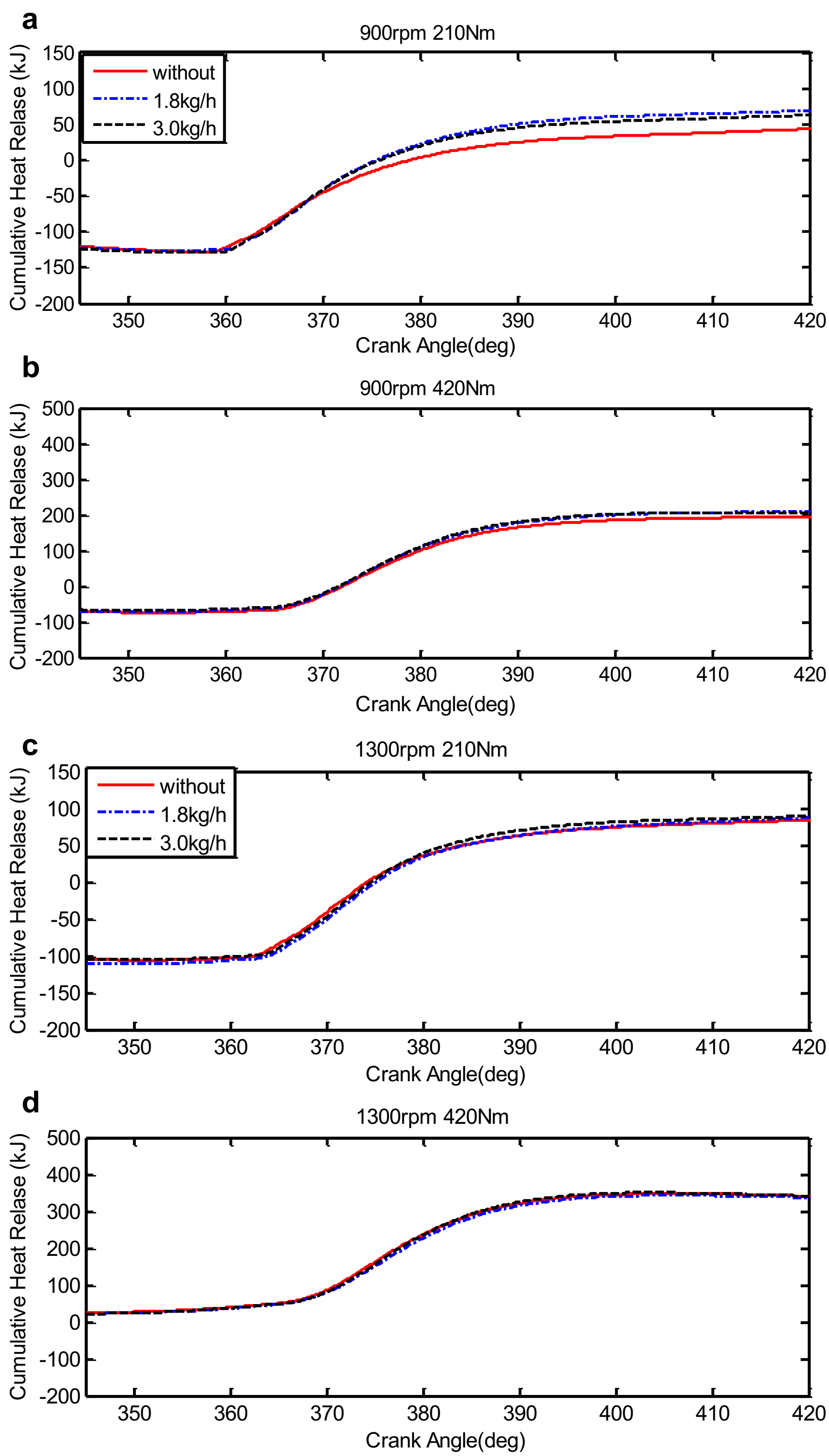

Fig. 7. Cumulative heat releases at 1300 rpm and different loads.

flow rate increases the NO_x emission also reduces proportionally. The water injection into the intake manifold reduces the NO_x exhaust emission by around 30% and 50% at 1.8 kg/h and 3 kg/h water injection rates respectively as shown in Fig. 12(b) and (d). This phenomenon can be explained on the basis that as water—air mixture is injected into the combustion chamber, some of the heat is absorbed by the water during the process of water vaporisation. The process reduces the peak flame temperature of the combustion chamber which negatively impacts formation of nitrogen oxides (NO_x) emissions. In addition, the water injection at cylinder chamber changes the thermo-physical properties of water which has an effect on the heat transfer coefficient of the gas mixture and facilitates the heat loss through the walls of the cylinder.

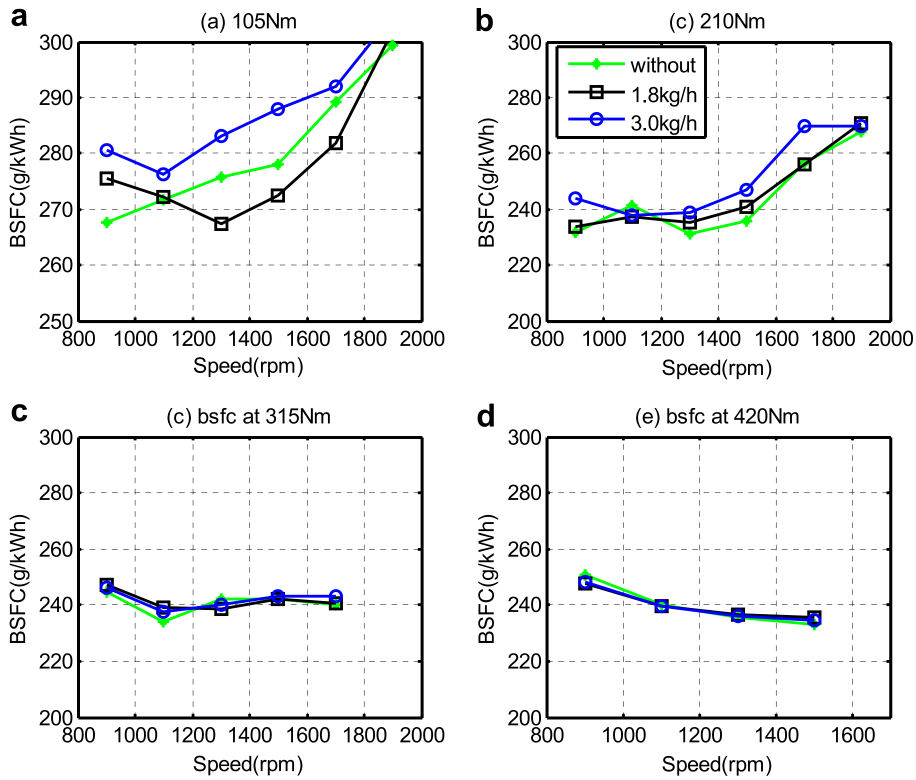

Fig. 8. Brake specific fuel consumption (bsfc) at different loads.

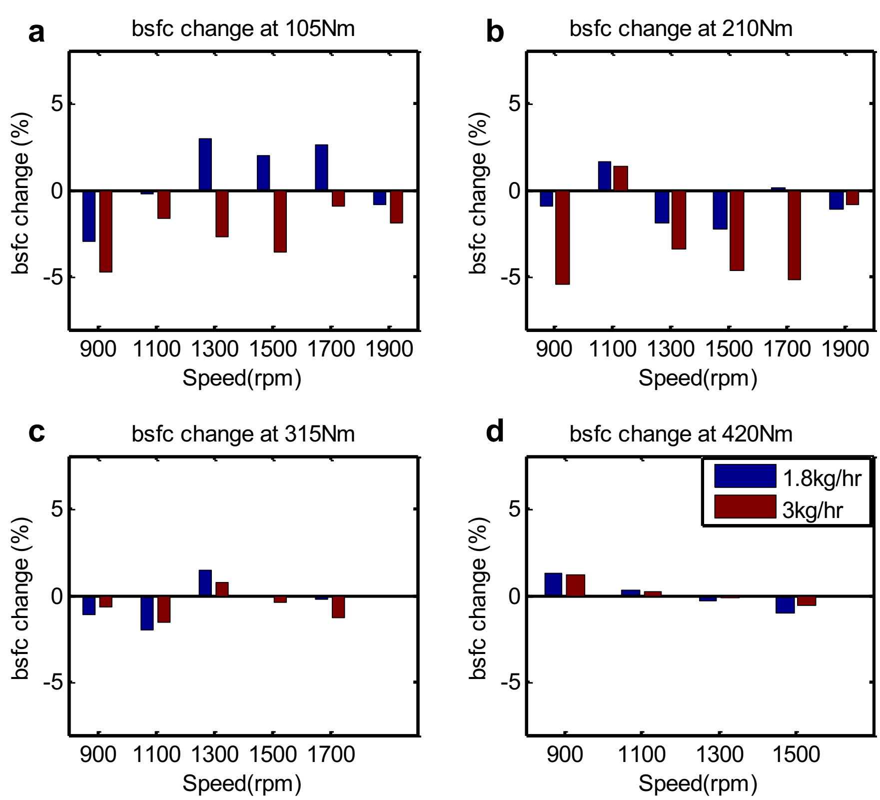

Fig. 9. Brake specific fuel consumption (bsfc) at different loads.

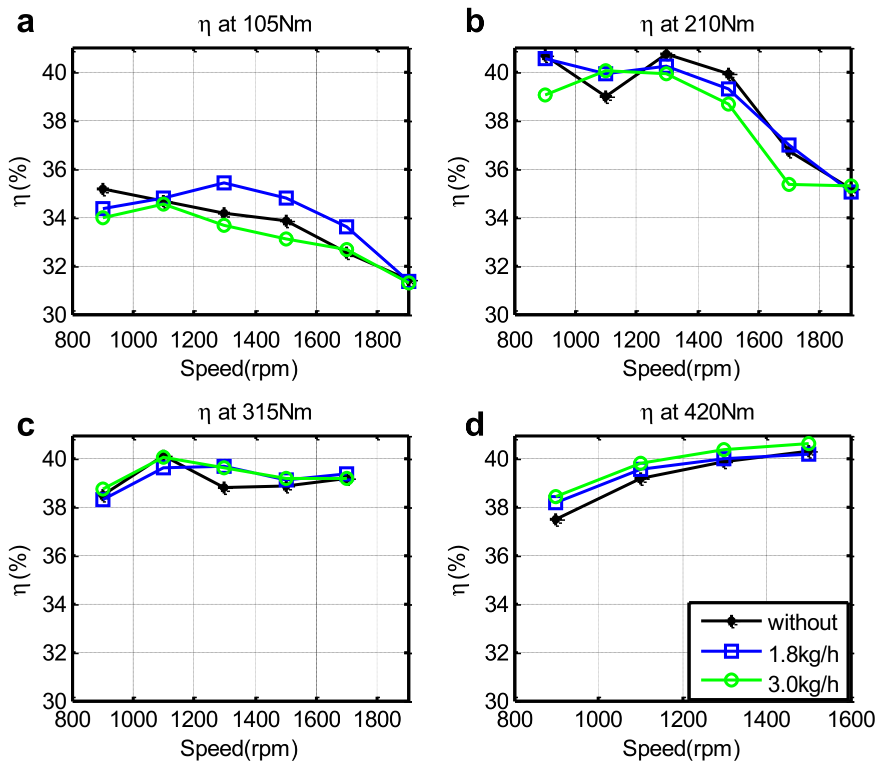

Fig. 10. Brake specific fuel consumption (bsfc) at different loads.

Fig. 13 shows the effect of water injection on the CO emission at various engine speeds and at two different loads of 105 Nm and 315 Nm loads. It can be seen that at higher water flow rate (3 kg/h) the CO emission increases at all operating conditions. There are two main reason for increase in CO emission, firstly the reduction of the pre-combustion temperature due to water injection slows the chemical conversion of the CO to CO_2; secondly the solid carbon reaction at high temperature with water vapour enhances the formation of CO and H_2O in the cylinder. It also seen that when the engine speed and load increase the CO emission decreases. These is because at higher engine speeds the air/fuel equivalence ratios increases and this result in an increase in the in-cylinder gas temperature, which leads to increase in the kinetic reaction rate from CO to CO_2.

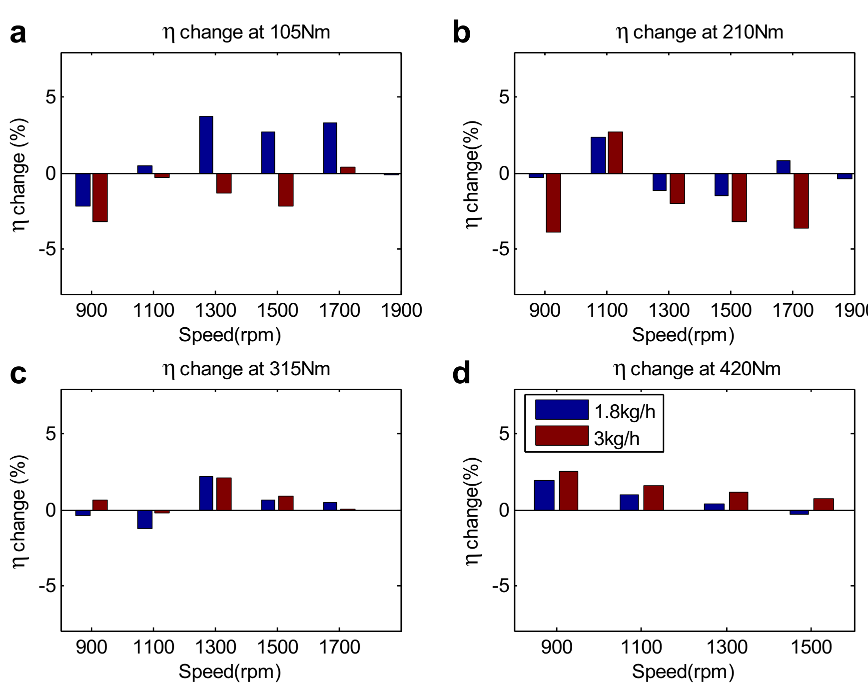

Fig. 11. Brake specific fuel consumption changes.

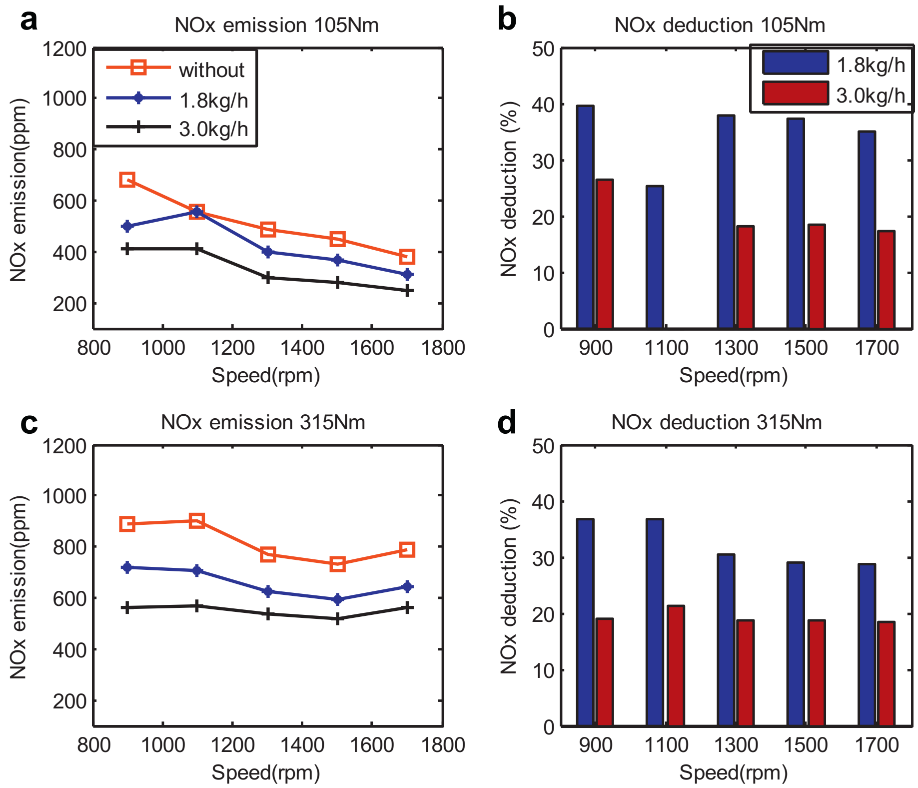

Fig. 12. NO_x emission and percentage reduction.

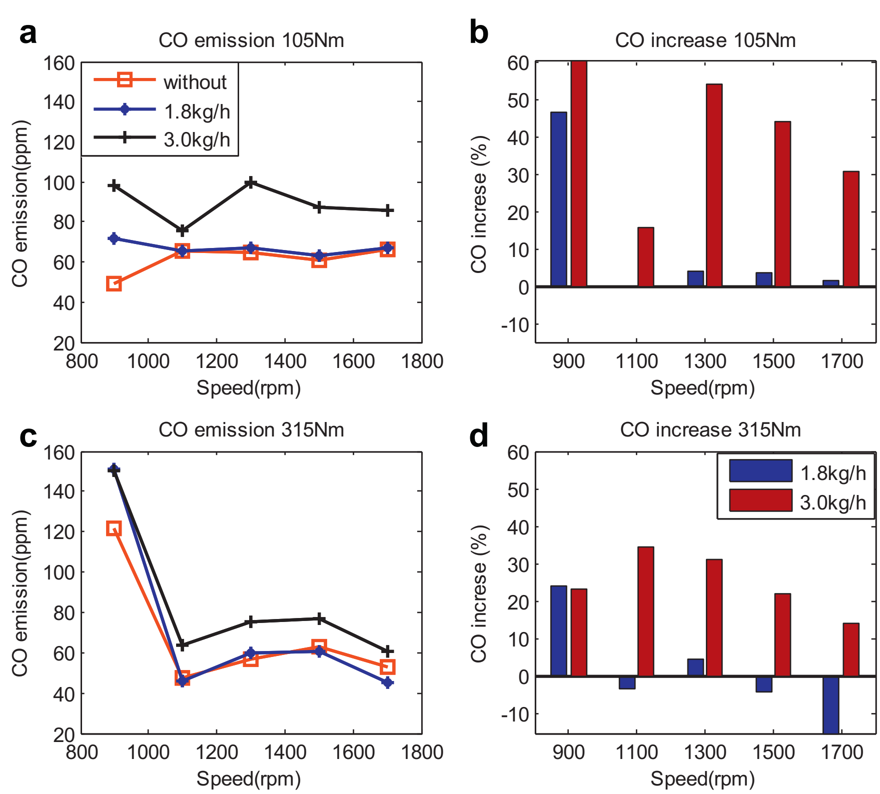

Fig. 13. CO emission and percentage increase.

5. Conclusion

In the present study an experimental investigation has been carried out on the combustion, performance and emission characteristics of a CI engine running with biodiesel with an integrated water injection system under steady state operating conditions. Based on the experimental results the main effects of the water injection are summarized as follows:

1. The water injection at the intake manifold does not indicate any significant difference on the peak cylinder pressure and heat release rate of CI engine running with biodiesel. The results show that the water injection at the intake manifold may not affect the peak temperature; instead it affects the premixed combustion temperature which is mainly the cause of NO_x emission.
2. The water injection at intake manifold does not show any significant change in the brake specific fuel consumption and thermal efficiency of the engine at intermediate and higher engine loads. However, it was seen that the brake specific fuel consumption increased by a maximum of 4% and the thermal efficiency decreased by a maximum of 3% at low loads due to the water injection.
3. The water injection into the intake manifold reduces the NO_x emission by up to 50% over the entire operating range. However, the CO emission increases by about 40%.
4. Based on the above it can concluded that water injection into the intake manifold can be employed to reduce NO_x emission without loss of power and any negative effect on fuel consumption.

References

[1] Nabi MN, Hustad JE. Influence of biodiesel addition to Fischer–Tropsch fuel on diesel engine performance and exhaust emissions. Energy & Fuels May. 2010; 24(5):2868–74.

[2] Tauzia X, Maiboom A, Shah SR. Experimental study of inlet manifold water injection on combustion and emissions of an automotive direct injection diesel engine. Energy Sep. 2010;35(9):3628–39.

[3] Bayraktar H. Experimental and theoretical investigation of using gasoline-ethanol blends in spark-ignition engines. Renewable Energy Sep. 2005; 30(11):1733–47.

[4] Fernando S, Hall C, Jha S. NO_x reduction from biodiesel fuels. Energy & Fuels Jan. 2006;20(1):376–82.

[5] Hammond G, Kallu S, McManus M. Development of biofuels for the UK automotive market. Applied Energy Jun. 2008;85(6):506–15.

[6] Lapuerta M, Armas O, Ballesteros R, Fernàndez J. Diesel emissions from biofuels derived from Spanish potential vegetable oils. Fuel Apr. 2005;84(6): 773–80.

[7] Durbin T, Collins J, Norbeck J, Smith M. Effects of biodiesel, biodiesel blends, and a synthetic diesel on emissions from light heavy-duty diesel vehicles. Environmental Science & Technology Feb. 2000;34(3):349–55.

[8] Puppan Daniel. Environmeental evaluation of biofules [Online]. Available: http://www.pp.bme.hu/so/2002_1/pdf/so2002_1_08.pdf; 16-Jun [accessed: 16.06.08].

[9] Ramadhas A, Muraleedharan C, Jayaraj S. Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. Renewable Energy Oct. 2005;30(12):1789–800.

[10] Dorado MP, Ballesteros E, Arnal JM, Gömez J, Löpez FJ. Exhaust emissions from a Diesel engine fueled with transesterified waste olive oil [small star, filled]. Fuel Jul. 2003;82(11):1311–5.

[11] Utlu Z, Koçak MS. The effect of biodiesel fuel obtained from waste frying oil on direct injection diesel engine performance and exhaust emissions. Renewable Energy Aug. 2008;33(8):1936–41.

[12] Lapuerta M, Armas O, Rodríguez-Fernández J. Effect of biodiesel fuels on diesel engine emissions. Progress in Energy and Combustion Science Apr. 2008; 34(2):198–223.

[13] Graboski MS, McCormick RL. Combustion of fat and vegetable oil derived fuels in diesel engines. Progress in Energy and Combustion Science 1998;24(2): 125–64.

[14] Belachew T, Rakesh M, Gu F. Emission behavior of a CI engine running by biodiesel under transient conditions, vol. 2010. SAE; 2010.

[15] Lin C, Lin H. Diesel engine performance and emission characteristics of biodiesel produced by the peroxidation process. Fuel Feb. 2006;85(3): 298–305.

[16] E. EU, "European emission standard," Diesel Net.

[17] Dieselnet, "Emission standards: Europe: cars and light trucks." [Online]. Available: http://www.dieselnet.com/standards/eu/ld.php. [accessed: 29.09.10].

[18] Ibrahim A, Bari S. A comparison between EGR and lean-burn strategies employed in a natural gas SI engine using a two-zone combustion model. Energy Conversion and Management Dec. 2009;50(12):3129–39.

[19] Rodríguez-Fernández J, Tsolakis A, Cracknell R, Clark R. Combining GTL fuel, reformed EGR and HC-SCR aftertreatment system to reduce diesel NO_x emissions. A statistical approach. International Journal of Hydrogen Energy Mar. 2009;34(6):2789–99.

[20] Agrawal AK, Singh SK, Sinha S, Shukla MK. Effect of EGR on the exhaust gas temperature and exhaust opacity in compression ignition engines. Sadhana 2004;29(3):275–84.

[21] Martin B. Emissions control techniques applied to industrial vehicles [Online]. Available: http://www.ifp.fr/antidot/search?context=default&keywords=emission+control+techniques&x=0&y=0; 2005 [accessed: 17.07.10].

[22] Muller W, Klein H, Lox E, Kreuzer T, Ostgather K. Catalytic NO_x reduction on a passenger car diesel common rail engine, vol. 980191. SAE; 1998.

[23] Conklin JC, Szybist JP. A highly efficient six-stroke internal combustion engine cycle with water injection for in-cylinder exhaust heat recovery. Energy Apr. 2010;35(4):1658–64.

[24] Subramanian V, Mallikarjuna J, Ramesh A. Effect of water injection and spark timing on the nitric oxide emission and combustion parameters of a hydrogen fuelled spark ignition engine. International Journal of Hydrogen Energy Jun. 2007;32(9):1159–73.

[25] Radloff E. NO_x emissions reduction through water injection. Naval Engineers Journal 2006;118(3):65–76.

[26] Hountalas D, Mavropoulos G, Zannis T, Mamalis S. Use of water emulsion and intake water injection as NO_x reduction techniques for heavy duty diesel engines. SAE 2006-01-1414; 2006.

[27] Breda K, Stanislav P. Reduction of diesel engine emissions by water injection. SAE 2001-01-3259; 2001.

[28] Andrews G, Bartle K, Pang S, Nurein A, Williams P. The reduction in diesel particulate emissions using emulsified fuels, vol. 880348; 1988.

[29] Park J, Huh K, Park K. Experimental study on the combustion characteristics of emulsified diesel in a rapid compression and expansion machine. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2000;214(5):579–86.

[30] Samec N, Kegl B, Dibble RW. Numerical and experimental study of water/oil emulsified fuel combustion in a diesel engine. Fuel Nov. 2002;81(16): 2035–44.

[31] Lin C, Chen L. Engine performance and emission characteristics of three-phase diesel emulsions prepared by an ultrasonic emulsification method. Fuel 2006; 85(5):593–600.

[32] Selim MYE, Elfeky SMS. Effects of diesel/water emulsion on heat flow and thermal loading in a precombustion chamber diesel engine. Applied Thermal Engineering Oct. 2001;21(15):1565–82.

[33] Kadota T, Yamasaki H. Recent advances in the combustion of water fuel emulsion. Progress in Energy and Combustion Science 2002;28(5):385–404.

[34] Stanglmaier RH, Dingle PJ, Stewart D. Cycle-Controlled water injection for steady-state and transient emissions reduction from a heavy-duty diesel engine. Journal of Engineering Gas Turbines and Power 2008;130(3).

[35] Chadwell CJ, Dingle PJ. Effects of diesel and water co-injection with-real control time control on diesel engine performance and emission. SAE Peper 2008011190; 2008.

[36] Armas O, Ballesteros R, Martos F, Agudelo J. Characterization of light duty diesel engine pollutant emissions using water-emulsified fuel. Fuel May. 2005;84(7):1011–8.

[37] Sawa N, Kajitani S. Physical properties of emulsion fuel (water/oil-type) and its effect on engine performance under transient operation, vol. 920198; 1992.

[38] M. Gumus, "A comprehensive experimental investigation of combustion and heat release characteristics of a biodiesel (hazelnut kernel oil methyl ester) fueled direct injection compression ignition engine," Fuel.

[39] Brusca S, Lanzafame R. Evaluation of the effects of water injection in a single cylinder CFR Cetane engine. SAE; 2001. Paper No 2001-01-2012.

[40] Abu-Zaid M. Performance of single cylinder, direct injection diesel engine using water fuel emulsions. Energy Conversion and Management Mar. 2004; 45(5):697–705.