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Effect of Water Injection into Exhaust Manifold on Diesel Engine Combustion and Emissions

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Abstract

In this study, an experimental investigation was conducted to assess the combustion and emissions of a single cylinder diesel engine using water injection in the exhaust manifold. Water is injected into the exhaust manifold and by opening the exhaust valve during the intake stroke, the injected water, and exhaust gases are reentered the engine cylinder then mixed during the intake and compression stroke and participated in the combustion process. The purpose of this injection strategy is to utilize the exhaust gases enthalpy to evaporate water before combustion to reduce soot and NO_x emissions without decrease combustion temperature. The results show that water injection leads to increase in the cylinder pressure, apparent heat release rate (AHRR) in premixed combustion phase and, the ignition delay comparing with EGR without water injection. The indicated mean effective pressure (IMEP) for EGR without water injection is lower than conventional diesel combustion with 14 %. However, with water injection, the IMEP increased with 11% comparing to EGR without water injection. NO_x emissions reduced up to 85% comparing to conventional diesel combustion due to the EGR effect. Soot concentration increased dramatically with EGR. However, with water injection, soot emissions reduced by up to 40% but still higher than conventional diesel combustion.

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Keywords: Diesel Engine; Water injection; Combustion control; Emissions; Exhaust gas recirculation

Nomenclature

AHRR	Apparent Heat release rate	IVC	Intake Valve Close
ATDC	After Top Dead Center	IVO	Intake Valve Open

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BDC	Bottom Dead Center	NO_x	Nitrogen Oxides
CO	Carbon Monoxide	OH	Hydroxyl group
EGR	Exhaust Gas Recirculation	PM	Particulate Matter
EVC	Exhaust Valve Close	Ppm	Part Per Million
EVO	Exhaust Valve Open	SOI	Start of Injection
FPGA	Field Programmable Gate Array	VVA	Variable Valve Actuating
HC	Hydrocarbon	WI	water injection
IMEP	Indicate Mean Effective Pressure		

1. Introduction

Diesel engines are widely used in transportation systems and power generation and play a major role in influencing fuel economy as well as contribute to the environmental impact of air pollution significantly. Nitrogen oxides NO_x and soot are the predominant pollutants from diesel engines. Additionally, Growing concerns about fossil fuel depletion and recent tendency towards more strict regulations on emissions have been a significant incentive for improving the fuel efficiency and reducing in-cylinder emissions. Water injection is one of the used in-cylinder strategies aiming to control the diesel combustion and emissions and has studied for decades. Water injection has various effects on diesel combustion such as the dilution effect, the thermal effect, and the chemical effect and all of them contributed to NO_x and soot reduction [1 – 12]. The decrease in soot and PM emissions with water injection was reported as a result of the dilution effect which occurs due to micro-explosions or sudden expansion caused by the disruptive effect of water vaporizing within the fuel droplets during the droplet heating period [1]. Also, the reduction of PM and soot emissions was explained due to the increase in total injected mass that increases the mixing rate between fuel and air. Consequently, the mass fraction of the fuel that burns under premixed condition increased [2]. The water thermal effect is defined as the injected water getting the latent heat of vaporization from the heat released during the combustion results in lower heat release and flame temperature. The water thermal effect is due to the high latent heat of vaporization and specific heat capacity of injected water and results in decreasing the diesel flame temperature and consequently the thermal NO_x [6], [8], [9], [10], and [11]. The chemical effect was explained as the water addition leads to increase in OH radicals that might have a significant impact in soot oxidation and reduce the soot formed in the gas phase [1], [12]. However, the three effects are related as the dilution of water vapour may terminate the chemical reaction in the gas phase due to the reduced apparent heat release rate (AHRR). The suppression of the chemical reaction might cause a reduction in flame temperature and consequently a reduction of thermal NO_x emissions [12].

There are three ways to introduce water into the engine cylinder. Firstly, by using water injection in the intake manifold. Secondly, by direct water injection in the engine cylinder using a separate injection pump and the injection nozzle. Also, by water injection directly into the cylinder through the fuel injection nozzle either by a separate injection pump or by water and fuel emulsion [1], [4], and [7]. Many researchers investigated the injection of water in the intake manifold. The water/fuel ratio increased up to maximum 65% [4]. They reported that water to fuel mass ratio of 60-65% is needed to obtain a 50% NO_x reduction. Most studies show a decrease in NO_x with a slight increase in PM emissions and increase in CO and HC emissions while increasing the water quantity that uses the in-cylinder heat release to evaporate and reduce the flame temperature [4]. Also, a decrease of in-cylinder mean pressure and burning rate reported with water injection combined with an increase in the combustion duration [6]. Additionally, Ignition delay increased with water injection which leads to a significant fraction of premixed burning, higher rates of cylinder pressure rise, and increased combustion noise [1]. This technique suffers from the drawback that the liquid water in the combustion chamber is typically in areas where it is less efficient to reduce emissions. Therefore, this method requires approximately twice the liquid volume for the same reduction in NO_x comparing to direct water injection. Additionally, liquid water present after combustion can contaminate the oil and increase engine wear [7]. One advantage of in-cylinder direct water injection as compared with water/diesel emulsion is the possibility to change the water/fuel ratio, while varying engine speed and load [7]. This system shows a considerable improvement in both NO_x and PM emissions. However, the disadvantage of this technique is that water injector should be added to the engine cylinder [1]. Additionally, the co-injection required a more advanced control system that capable of injecting both of water and fuel in different quantity using the same injector. Also, the amount of mixing inside the injector is not well known and can vary with the design of the injector body [7]. Diesel/water emulsion studied in [5], [8], [9], [10], [11] and[12]. Abu Zaid [5] investigated the water/diesel emulsion of 0, 5, 10, 15 and 20 water/Diesel ratios by volume. Abu Zaid reported that the addition of water in the form of emulsion improved combustion efficiency, engine torque, power and brake thermal efficiency. Also, the brake specific fuel consumption and exhaust gases temperature decrease as the percentage of water in the emulsion increases. Maiboom and Tauzia [2] studied the water/diesel emulsion with a volumetric ratio of 25.6%. They cited that using water/diesel emulsion technique show that the NO_x reduction accompanied by a large reduction of PM and soot emissions. The emulsified fuel technique results in lower the flame temperature. The early lowering of flame temperature can lead to increased ignition delay and engine noise. Additionally, different engine operating conditions and loads may require different blends of fuel and water which are not possible as the emulsion blend is constant [5]. Water injection in the intake manifold or direct water injection can overcome this disadvantage [7]. For the water chemical effect on soot oxidation, the relation between the OH radical and soot oxidation has been studied through [13, 14]. Kosaka et al. [13] concluded that OH radical generated in the flame reacts immediately with soot particles, and the burning progresses at the soot surface; consequently, both soot particles and OH radicals cannot coexist. The relation between the normalized soot number density and OH radical in-cylinder was described by Fujimoto et al. [14]. They cited that the normalized soot number density shows the maximum when OH radical starts to be detected, and it decreases with increase in OH emission. OH radical immediately forms just after the ignition and used in the oxidation of soot and other hydrocarbons.

In the present experimental study, new water injection strategy is proposed to overcome the disadvantages in previously studied techniques. The water is introduced into the engine cylinder through injecting water into the exhaust manifold to utilize the enthalpy of exhaust gases to evaporate injected water. By opening the exhaust valve during the intake stroke, the evaporated water, and exhaust gases flow into the cylinder, mixing with the fresh air during the compression stroke and participate in the combustion. The main objective here is to avoid water evaporation in the cylinder and subtract the water latent heat of vaporization from the heat released during the combustion process. The effect of in-cylinder water evaporation and reducing combustion heat release named as thermal effect and leads to reduce the flame temperature. The water injection strategy used in this study aims to reduce the thermal effect and study other effects such as chemical and dilution effects of water vapour on diesel combustion that is expected to promotes soot oxidation by increasing the intensity of OH radical. Additionally, study the effect of water vapour on NO_x formation through a dilution effect. Also, the effects of water injection amount and timing in exhaust manifold in addition to EGR ratio are studied at different operating conditions.

2. Experimental Setup

The experimental work was conducted using a four-stroke water-cooled single-cylinder diesel engine. A schematic diagram of the experimental setup is shown in Fig.1, and the engine specifications are listed in Table 1. This engine is equipped with a common rail fuel injection system, supercharger, the variable valve actuating VVA system, and external EGR system. The supercharger is using a separate compressor that driven by an independent motor. Thus, the intake pressure can be controlled independently. Similarly, the variable valve actuating system is driven by a hydraulic system. Therefore, intake and exhaust valves timing and displacement are also operated independently. The internal EGR ratio is controlled by the movement of exhaust valve during the intake stroke. Also, a pressure control valve is installed after exhaust manifold to allow boosting of exhaust pressure and also controlling the EGR ratio. The water injector is mounted on the exhaust manifold, and high-pressure water pump supplies the water. The water injection system can control the water injection timing and quantity. Water injection quantity was measured by the direct sampling method at different injection durations. The engine is also equipped with pressure sensors to measure the intake pressure and exhaust pressure. The piezoelectric pressure transducer Kistler 6123 is used to measure the cylinder pressure. K-Type thermocouples are placed in the piping at various locations throughout the system to monitor the intake air temperature, exhaust temperature, lubricant oil temperature, external EGR temperature and cooling water temperature. Rotary encoder and the photo sensor are installed to measure engine speed, crank angle and detect TDC, which are also necessary for sampling of cylinder pressure and for controlling injection timing and valve timing. Labview software and FPGA board are used for the control of system and data acquisition. For exhaust emissions measurement, the smoke meter is used for soot concentration measurement. The electric heater with a thermal controller is installed in the soot sampling line to control the sampling line temperature at 200° C. For NO_x measurement, MEXA-720 NO_x sensor provides fast-response measurements of NO_x concentrations.

Table 1. Engine Specification

Engine Type	4-Stroke Single Cylinder DI Diesel Engine
Bore	89mm
Stroke	100mm
Displacement	622 cm^3
Compression Ratio	15.0
Combustion Chamber	Reentrant type
Injection System	Common Rail Injection System
Injection Nozzle	Φ 0.158mm × 8
Intake System	Supercharged
Valve Train	2 Intake Valves and One Exhaust Valve

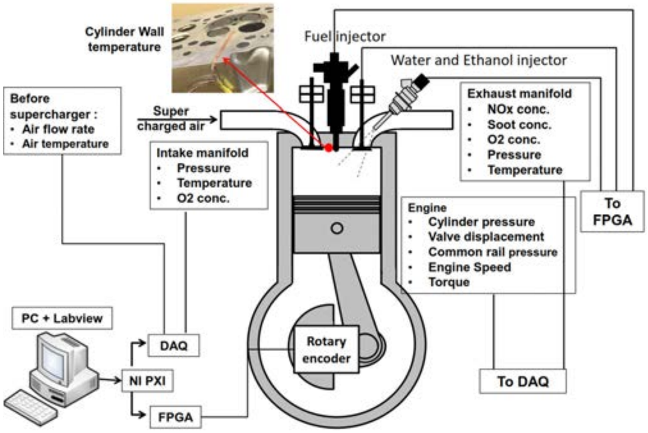


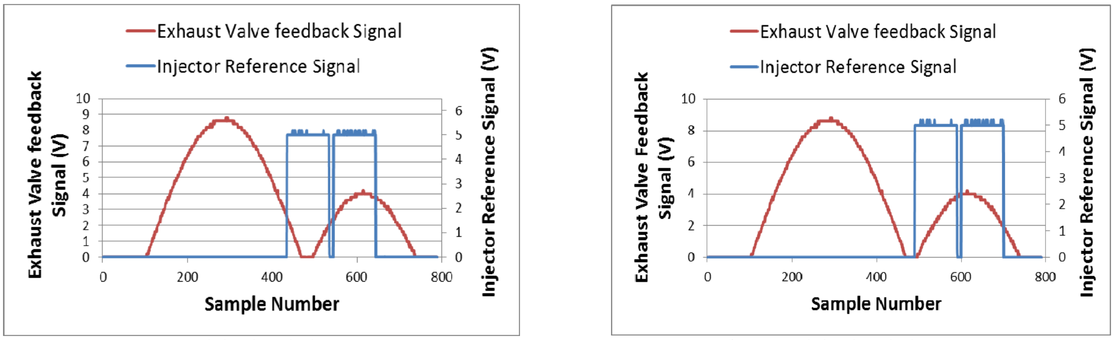
Fig.1. Schematic diagram for experimental setup and measurements

3. Results and Discussions

The water injection strategy used in this study includes injection of water into the exhaust manifold. Then, the exhaust valve was opened during the intake stroke to introduce the evaporated water to the engine cylinder. The fuel is directly injected into the combustion chamber at -6°ATDC as shown in Table 2. Since the combustion pressure, AHRR and ignition delay are influenced by intake temperature, fuel injection timing, fuel quantity, cooling water temperature, and lubricant oil temperature, these parameters controlled at constant values during the experiment as shown in Table 2 for the experimental condition. The variables in this study are water injection timing, EGR ratio, CA50 control and water injection quantity.

Table 2. Experimental conditions

Engine speed [rpm]	1000
Fuel Injection quantity [mg/cycle]	32
Fuel Injection timing [ATDC]	-6
Water Injection timing [0 -720 deg] SOI	350°, 400°
Water Injection amount [mg/cycle]	6, 12, 24 and 40
Intake air temp	65°C
Coolant temp	85°C
Oil temp	70°C
Intake valve lift, IVO, IVC	8 mm,14° BTDC, 30°ABDC
Exhaust valve lift, EVO, EVC	8 mm, 39° BBDC , 5°ATDC
Exhaust valve reopen lift [mm] and EGR ratio [%]	3mm (10% EGR) and 4mm (25% EGR)
Equivalence ratio for the conventional diesel combustion	0.72

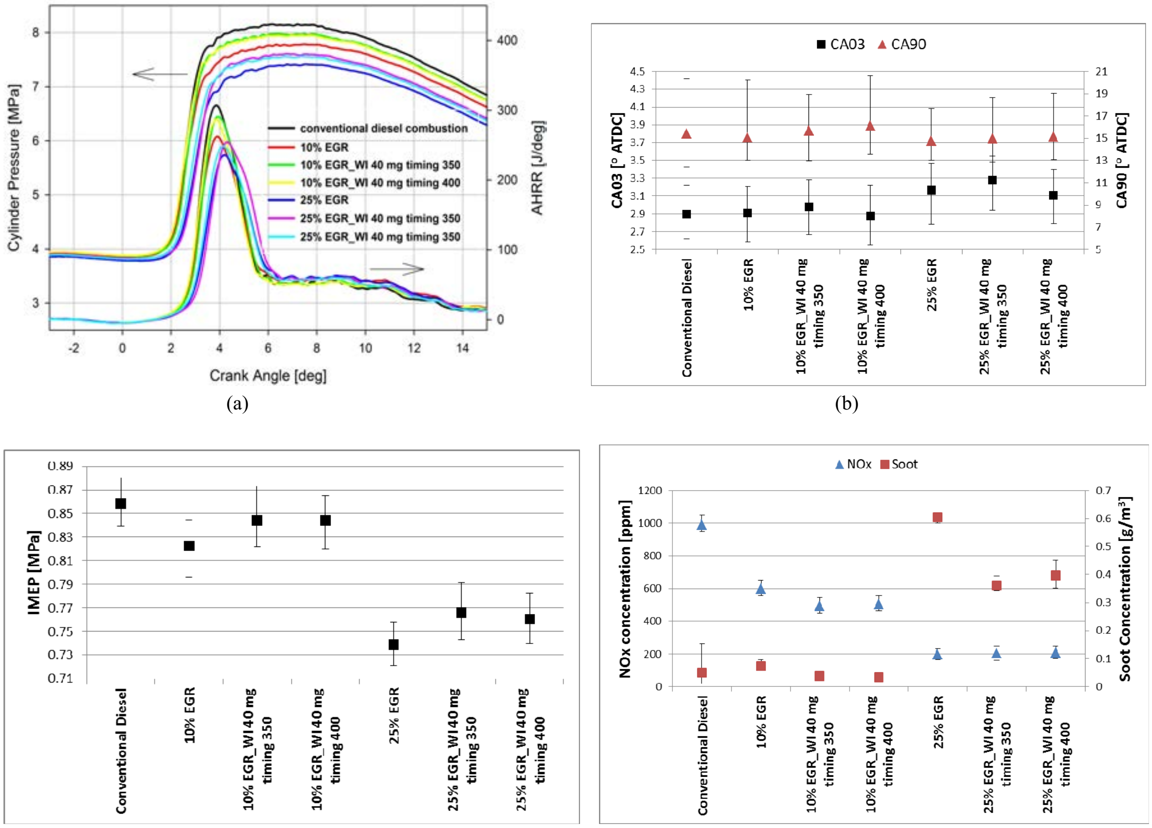


(a) Water injection timing of 350° (b) Water injection timing of 400°

Fig.2. Water injector reference signal and exhaust valve opening and reopening feedback at different injection timing (a) 350° ;(b)400°

3.1. Effect of water injection at different timing and different EGR ratio

The effect of water injection timing on combustion process is to discuss in this section. Therefore, the water injected amount is fixed at 40 mg/cycle, while, the different two water injection timings of 350° and 400° are adopted as shown in fig.2. The higher peaks are shown in fig.2 (a) and (b) are the standard opening of the exhaust valve of 8mm at the exhaust stroke, and the lower peak is for the reopening of the exhaust valve during the intake stroke in order to introduce the injected water to the cylinder. Also, the water injector reference signal is shown with the valve timing and displacement at fig.2 to see the difference between the two tested injection timings. To better understanding the effect of water injection on combustion, soot, and NO_x formation, discussion conducted to distinguish between the EGR effect and water injection effect. Therefore, at each tested water injection condition, EGR without water injection case is tested. The EGR ratio is depending on the exhaust valve lift during the intake stroke. In this section, 3mm and 4 mm exhaust valve reopening are used corresponding to 10% EGR and 25% EGR ratio respectively. Figure 3 (a) shows the comparison between the AHRR and combustion pressure data at different water injection timings and exhaust valve reopening lifts. The combustion pressure decreases with 5.7% and 10.6% by increasing the EGR ratio to 10% and 25% respectively. However, by comparing water injection effect with EGR without water injection, the combustion pressure slightly increase by 3.3% and 2.5% in average for 350° and 400° injection timing at 10% EGR ratio and by 3% and 2.2% in average for 350° and 400° injection timing at 25% EGR ratio. Previous studies show a reduction in cylinder pressure with water injection caused by the heat absorption due to water evaporated. The increasing in cylinder pressure in the current study may be due to that water is evaporated in the exhaust manifold by using the enthalpy of exhaust gas. This system is a kind of regeneration of the wasted energy, in which the part of exhaust enthalpy is returned to the combustion chamber and enhance the combustion in the next cycle. However, the cylinder pressure with water injection still lower than that of conventional diesel combustion due to the EGR effect. Similarly, the AHRR curve shows that the peaks of premixed combustion phase for water injection conditions are higher than that of EGR without water injection. For mixing control combustion phase, the AHRR is slightly higher for EGR and water injection conditions comparing with conventional diesel combustion and lower than conventional diesel combustion for the late combustion phase. Combustion phasing of CA03, CA50, and CA90, at the various conditions are shown in fig.3(b). CA03 is defined as the crank angle at which the 3% of the total heat is released during the combustion and used as an indicator for the start of the combustion process and for estimating the ignition delay. Also, CA50 and CA90 are defined as the crank angle at which the 50% and 90% of the total heat released during the combustion and CA90 indicates the end of combustion. As shown in fig.3(b) CA03 is longer for EGR without water injection comparing to the conventional diesel with 0.0112° for 10% EGR ratio and 0.26° for 25% EGR ratio. However, the CA03 for water injection timing of 350° is increased with 0.079° and 0.38° for 10% and 25% EGR ratio respectively while it decreases with 0.019° for 10% EGR and increases with 0.21° with 25% EGR for water injection timing of 400°. The combustion duration is ranged from CA03 to CA90 as shown in fig.3 (b) and equal to 12.6°, 12.1° and 11.5° for conventional diesel, 10% EGR and 25% EGR without water injection, respectively. With water injection, the combustion duration increase to 12.7° and 13.2° for 350° and 400° water injection timing at 10% EGR comparing to conventional diesel combustion and increase to 11.7° and 12° for 350° and 400° water injection timing at 25% EGR comparing to 25% EGR without water injection. Water injection increases the duration between CA03 and CA90 comparing with other conditions without water injection. Figure 3(c) shows the IMEP for the same tested condition. The IMEP decreased with 10% EGR and 25% EGR with 4.1% and 14% comparing to that of conventional diesel combustion. With water injection, the IMEP increased with 2.6% and 2.7% for water injection timing of 350° and 400° at 10% EGR ratio and increased with 11% and 11.4% for water injection timing of 350° and 400° at 25% EGR ratio comparing with EGR without water injection.



(a) (b)

(c) (d)

Fig. 3. Effect of water injection timing and EGR ratio (a) cylinder pressure and AHRR; (b) combustion phasing CA03 and CA90; (c) IMEP; (d) Soot and NO_x emissions.

Figure 3(d) shows the soot and NO_x emissions. For 10% EGR ratio, NO_x emissions decreased with 40% comparing to conventional diesel combustion and by water injection, the reduction in NO_x emissions increased by 50% and 49% for water injection timing of 350° and 400°. The decrease in NO_x emission is 80% for all cases EGR ratio of 25%. This returns to that increase in EGR ratio decreases the inlet O_2 concentration leading to deceleration of mixing between O_2 and fuel resulting in an extension of the flame region. The gas quantity that absorbs the heat release increases and resulting in a lower flame temperature that results in lower thermal NO_x emissions. Soot emissions for 10% EGR ratio increased comparing to conventional diesel combustion with 44 % and decrease by water injection with 28% and 35% comparing to conventional diesel combustion for water injection timing of 350°

and 400°. For 25% EGR ratio, the soot emissions are greatly increased however with water injection, soot concentration decreased with 40% and 34 % for water injection timing of 350° and 400° comparing to 25% EGR case without water injection. The reduction in soot emissions with water injection comparing to EGR without water injection returns to dilution and chemical effects are responsible for soot reduction. Additionally, this injection strategy shows an effective way to reduce both of soot and NO_x emissions.

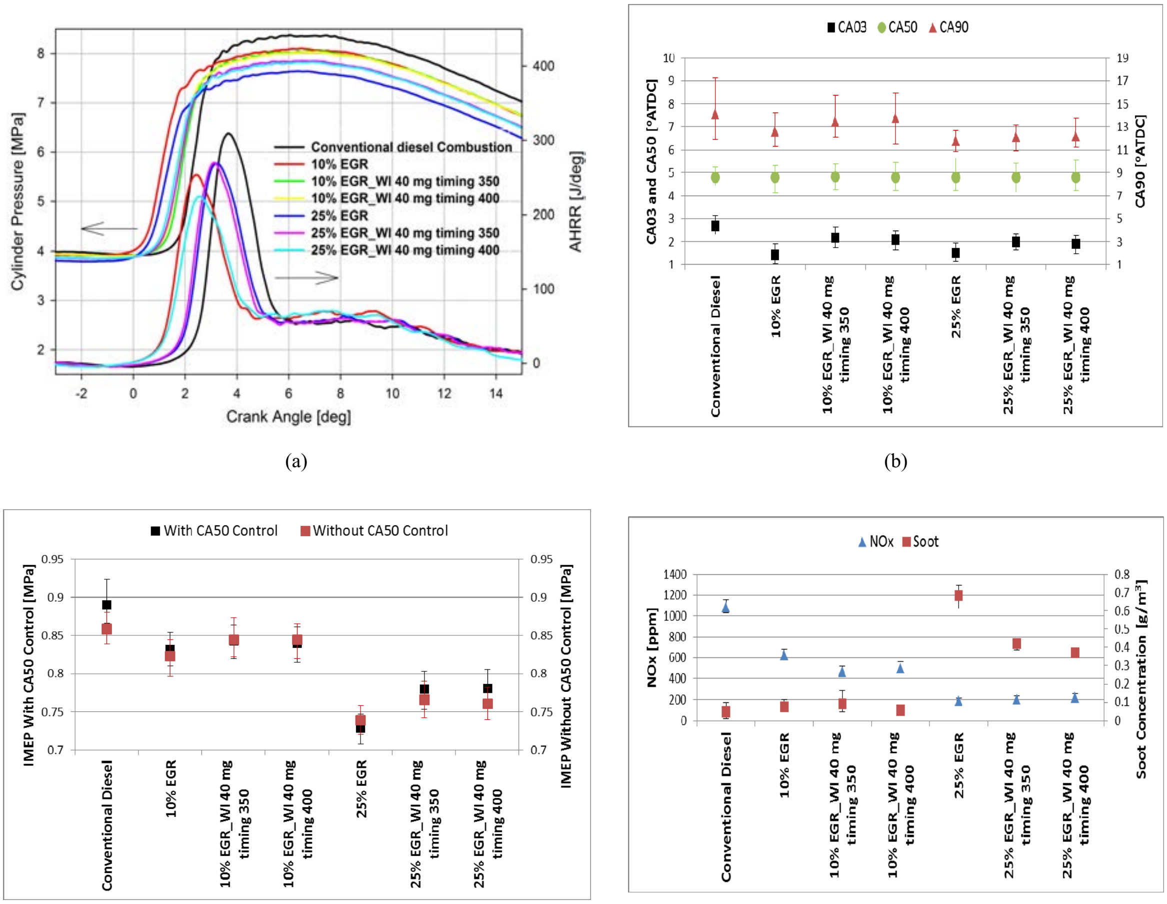
3.2. Effect of water injection with CA50 control

The previous section shows that water injection in exhaust manifold is effective for soot and NO_x reduction, however; the main disadvantage is the reduction in the IMEP. In this section, combustion phasing control is applied to control the CA50, which is defined as the crank angle at which the 50% of the total heat released during the combustion process. To control the CA50 at desired value, the CA50 is calculated at the engine control program for each cycle, and the start of injection of the fuel injector is adjusted accordingly. Therefore, the fuel start of injection timing is changed continuously to keep the CA50 at fixed value. In this study, CA50 for all the tested conditions is fixed at 4.8° ATDC as shown in fig.4(b) trying to increase the IMEP for water injection comparing to conventional diesel combustion. Also, the water injection quantity is fixed at this section at 40 mg/cycle. Cylinder pressure and AHRR is shown in fig.4(a). Water injection conditions have almost similar cylinder pressure as 10% EGR without water injection while the cylinder pressure for 25% EGR with water injection is higher than that of EGR without water injection. The combustion timing varied with the tested condition as the fuel injection timing is varied from cycle to cycle to fix the CA50 at 4.8° ATDC as shown in fig.4(b). The combustion duration from CA03 to CA90 equals to 11.4°, 11.2° and 10.2° for conventional diesel, 10% EGR and 25% EGR. For water injection, the duration from CA03 to CA90 equals to 11.3° and 11.6° for 10% EGR and equal to 10.1° and 10.3° for 25% EGR. Figure 4(c) shows improvement for IMEP after applying CA50 control comparing to without CA50 control. Applying CA50 control to 10% EGR with water injection achieves almost the same value for the same condition without CA50 control. On the other hand, the improvement of IMEP by the CA50 is clear at the condition without EGR (conventional diesel combustion). At the conditions of EGR ratio of 25 % with water injections, the improvement of IMEP by CA50 control is also observed. Figure 4(d) shows almost the same trends in NO_x and soot emissions with those in the case without CA50 control shown in fig.3(d). CA50 control does not influence the effects of EGR and water injection on emissions.

3.3. Effect of different water injection quantity

This group of experiments is conducted to evaluate the effect of water injection amount on engine combustion. Therefore, the injection timing and EGR ratio were fixed at 400° and 30% EGR. The water injection amount per cycle is ranged from 6 mg to 40 mg as listed in Table 2. Figure 5(a) shows the cylinder pressure and AHRR for different water injection amount. By increasing the amount of injected water, the maximum cylinder pressure increase comparing to EGR case with 1.3%, 1%, 2.4% and 3.8% for 6 mg, 12 mg, 24 mg and 40 mg water injection amount. However, comparing to conventional diesel combustion the EGR maximum combustion pressure is lower with 14%. Similarly, the peak of premixed combustion phase in AHRR curve is increased for water injection comparing with EGR without water injection. Figure 5(b) shows that the CA03 is increased with increasing the water injection amount. Additionally, the CA90 for water injection conditions is earlier than conventional diesel combustion and 30% EGR without water injection. The combustion duration from CA03 to CA90 are 9.3°, 9.2°, 9° and 9.4° for 6 mg, 12 mg, 24 mg and 40 mg, respectively compared to 9.5° and 11.8° for EGR without water injection and conventional diesel combustion.

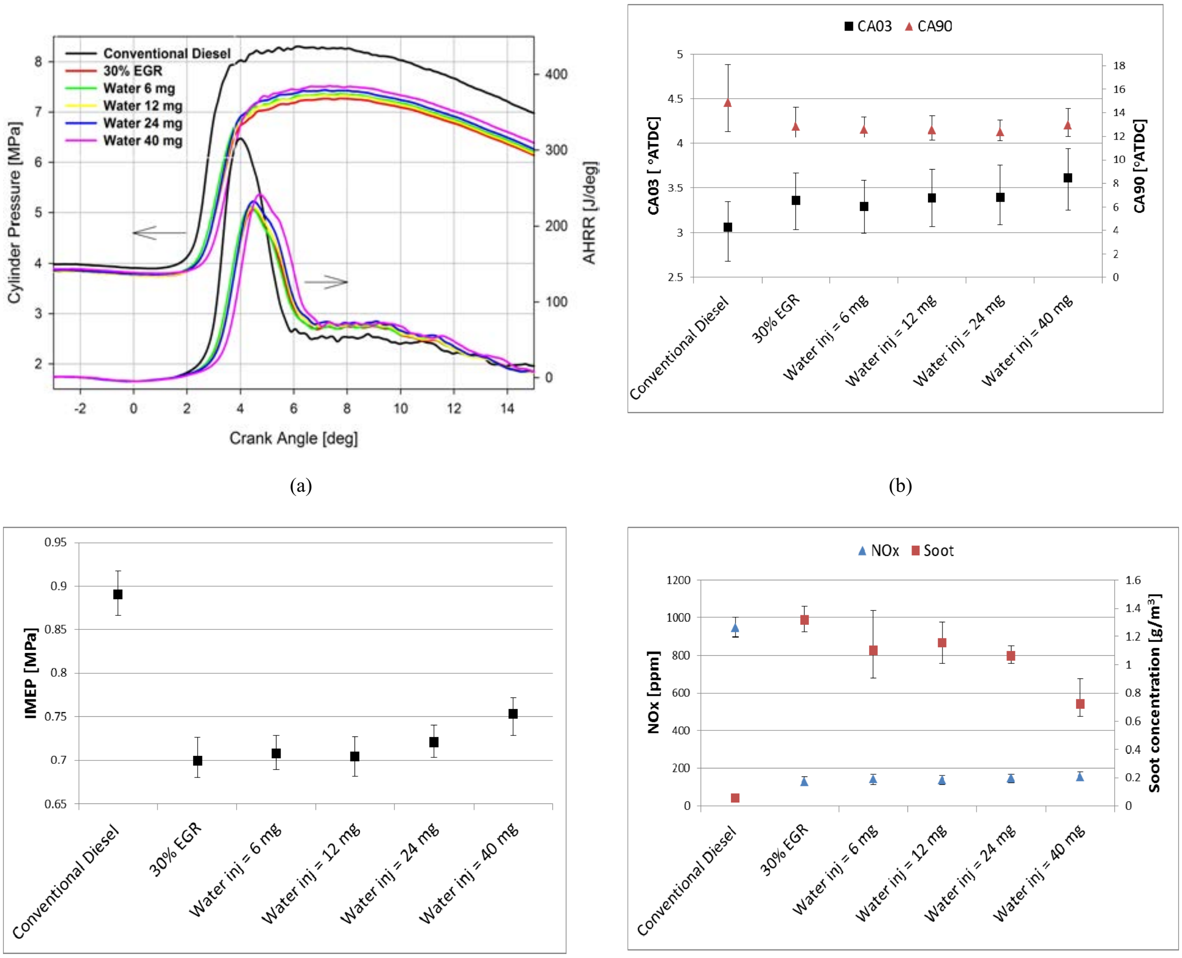
Figure 5(c) shows that the IMEP is reduced with 21.4% for 30% EGR without water injection. With water injection, the IMEP increased again by 1.1%, 0.6%, 3 % and 8% for 6 mg, 12 mg, 24 mg, and 40 mg respectively comparing to EGR without water injection. Figure 5(d) shows NO_x and soot emissions for all tested conditions. NO_x emissions reduced dramatically, with 85% in average for EGR without water injection and with water injection cases compared to conventional diesel combustion. Comparing to EGR without water injection, soot emissions gradually decreased with increasing the percentage of water injected amount. Soot concentration reduced with 16%, 12%, 19% and 45% for 6 mg, 12 mg, 24 mg, and 40 mg respectively comparing to EGR without water injection.



(a) (b)

(c) (d)

Fig. 4. Effect of CA50 control water injection on (a) cylinder pressure and AHRR; (b) combustion phasing CA03 and CA90; (c) IMEP with CA50 control and without CA50 control; (d) Soot and NO_x emissions.



(a) (b)

(c) (d)

Fig. 5. Effect of different water injection quantity on (a) cylinder pressure and AHRR; (b) combustion phasing CA03 and CA90; (c) IMEP; (d) Soot and NO_x emissions.

4. Conclusions

In this experimental study, the effect of water injection in exhaust manifold on combustion and emissions of the single cylinder diesel engine was investigated at different water injection timing, EGR ratio, and water injection quantity regarding engine combustion and emissions. The results can be summarized as following:

- Cylinder pressure is decreased by 5.7% and 10.6% for 10% and 25% EGR ratio respectively. By applying water injection at the same EGR ratio, cylinder pressure is increased by 3% in average comparing to EGR without water injection. The increase in cylinder pressure is a result of the introducing water vaporized by using the enthalpy of exhaust gas.
- The peak of premixed combustion phase at apparent heat release rate (AHRR) is slightly increased with water injection comparing to EGR without water injection. Also, increasing the water injection amount leads to longer ignition delay in most of the tested conditions.
- The IMEP is decreased by 4.1% and 14% with 10% EGR and 25% EGR comparing to that of conventional diesel combustion. With water injection, the IMEP is increased by 2.6% and 2.7% for water injection

timing of 350° and 400° at 10% EGR ratio and increased by 11% and 11.4% for water injection timing of 350° and 400° at 25% EGR ratio comparing with EGR without water injection.

- By applying CA50 control, the IMEP is not changed under the conditions of 10% EGR ratio. At the conditions of EGR ratio of 25 % with water injections, IMEP is improved by CA50.
- The NO_x emission is decreased by 40% for 10% EGR ratio and 80% for 25% EGR ratio and 85 % for 30% EGR ratio.
- Soot concentration is increased dramatically with increasing the EGR ratio. However, it can be decreased by 45% with applying water injection at the same EGR condition.
- The injection strategy investigated in this study is an effective way as evaporated water introducing into the combustion chamber and reusing of exhaust gas enthalpy, comparing other water injection techniques such as the intake manifold injection or direct water injection.

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