Applied Energy 260 (2020) 114328

Contents lists available at ScienceDirect

Applied Energy

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

New application to reduce NOx emissions of diesel engines: Electronically controlled direct water injection at compression stroke

Vezir Ayhan[a,*], Yılmaz Mert Ece[b]

[a] Sakarya University of Applied Sciences, Technology Faculty, Mechanical Engineering Department, Sakarya, Turkey
[b] Sakarya University of Applied Sciences, Department of Automotive Engineering, Graduate Education Institute, Sakarya, Turkey

HIGHLIGHTS

- Engine performance and emissions are examined for direct water injection.
- A 1 L naturally aspirated DI diesel engine has been used for the experiments.
- The optimum start of injection for water was 270°CA at the compression stroke.
- The optimum water ratio was determined to be 60% for performance emissions.
- With direct water injection, engine power increased and SFC decreased.

ARTICLE INFO

Keywords:
Engine performance
Water injection
Direct water injection
NOx
Combustion
Heat release
Emissions

ABSTRACT

In this study, the effect of Direct Water Injection (DWI) on the performance, emissions and combustion was experimentally investigated on a light-duty water-cooled direct injection, diesel engine. Water was injected into the combustion chamber under full load conditions with a dedicated water injector placed on the cylinder head at 10%, 20%, 40%, 60%, 80% and 100% of the fuel by mass, namely W10, W20, W40, W60, W80, W100, respectively. The injection quantity and start of injection in degrees crank angle (°CA) for water injector were controlled by an electronic control unit. Initially, standard engine values were obtained by fueling the engine with diesel fuel for full load condition, and then experiments were repeated at different DWI ratios. Reductions in NOx emissions up to 61% were obtained after applying DWI to the engine during the compression stroke. In addition, considerable improvements were observed in engine performance parameters. It was found out that, engine power increased by 3.7% and specific fuel consumption (SFC) decreased by 4.1%. There were not significant changes in exhaust gas emissions, CO and smoke, while hydrocarbon (HC) emissions increased. Considering all parameters, the optimum condition was obtained forW60-DWI ratio. It was determined that, the water injection performed during compression stroke decreased negative compression and increased cumulative heat release.

1. Introduction

Diesel engines have been widely preferred in many applications because they have higher efficiency and lower specific fuel consumption (SFC) [1]. However, the combustion characteristics increase nitrogen oxide (NOx) emissions quantities causing a serious environment pollution problem [2]. Therefore, to mitigate these issues and to meet the stringent emission regulations and besides efficiency improvement, researchers and engine manufacturers have used different options, such as renewable fuels [3,4], fuel blends [5,6], new combustion modes [7,8] a range of hardware-based strategies, particulate filters [9,10], exhaust gas recirculation, fast-response injectors, multiple injection strategies [11,12], variable valve timing during gas exchange [13,14] and injection of water into the engine cylinder [15,16]. On the other hand, the increase in energy consumption, causes the depletion of fossil fuels [17,18]. Thus, the diversification of energy resources and

Abbreviations: DI, direct injection; DWI, direct water injection; SFC, specific fuel consumption; PM, particulate matter; i-TDC, intake time top dead center; bTDC, before top dead center; rpm, revolutions per minute; NO, nitrogen monoxide; NOx, nitrogen oxides; CO, carbon monoxide; HC, hydrocarbon; STD, standard testing diesel; CA, degrees crank angle; W10, 10% water injection rate

* Corresponding author.
E-mail address: vayhan@subu.edu.tr (V. Ayhan).

https://doi.org/10.1016/j.apenergy.2019.114328
Received 12 September 2019; Received in revised form 2 December 2019; Accepted 3 December 2019

improvement of energy efficiency become important for the solution of this problem. Therefore, studies by automotive manufacturers and researchers focus on different methods to reduce NO emissions and increase fuel conversion efficiency to solve these problems which are major problems in the field of automotive industry [19,20].

The introduction of water into the combustion chamber of diesel engines has been considered as the most promising solutions to decrease NOx emissions and to improve the energy efficiency [21,22]. In fact, when water is injected into an engine combustion chamber, combustion temperatures decrease and considerable reductions are obtained in NOx emissions [23,24]. Water is generally delivered to an engine combustion chamber by three different methods: (a) emulsified fuels; prepared by mixing water and fuel in certain ratios simply (non-stabilized emulsified fuels) or with surface-active additive (stabilized emulsified fuels) [25–38], (b) fumigation; injection of water into the inlet manifold in liquid or gas phase [39,40], (c) direct injection; injection of water into the cylinder with a dedicated injector or a specially-designed integrated injector system for diesel and water [41,42]. In the direct injection method is advantageous, since water can be directly injected into the cylinder during compression stroke or on the flame front [43]. Thus, condensation risk is reduced by directly injection of water into the combustion regions of high temperatures, since water does not impinge on the cylinder walls [44]. Mixture amount adjustment problem regarding cold and transient operating conditions occurring in the case of using emulsified fuels, as well as, the corrosion risk in the inlet manifolds and on inlet valves occurring in the fumigation method are eliminated by the DWI method [45,46]. Moreover, the injection of water precisely and at the correct time at various ratios regarding different engine operating conditions is one of the most significant advantages of DWI method [42,47]. Although water can be considered more inert behaviour compared to fuel, it differs in characteristics, i.e. latent heat of vaporization and surface tension etc. when injected into the combustion chamber, significant reduction in NOx emissions and improvement in combustion efficiency is obtained [48,49]. In the case of emulsified fuels, micro-explosions occur due to vaporization of water at lower temperatures compared to fuel, resulting in the decomposition of fuel into droplets of much smaller diameters, and resulting to better atomization of fuel and formation of air-fuel mixture [50,51]. Improvements in the combustion energy and so in the performance parameters reasoning to water delivered into the engine [52,53]. As a result of the fumigation of water in the intake air, the density and air mass of the intake charge increase. In addition, combustion temperatures decrease as the heat capacity of work fluid increases [54,55]. Therefore, DWI is an effective NOx reduction method and has advantages over other methods. Arto et al. [42] investigated the effects of DWI application on engine emissions of a supercharged diesel engine. They reported significant decreases in NOx emissions, slight decreases in HCs and slight increases in Particulate Matter (PM) emissions by DWI.

In the literature, there have been numerous studies relating to the fumigation of water in intake air and the emulsified fuels. However, a few studies have been reported about DWI method. In this study, the effects of DWI at different ratios on engine performance parameters, combustion, heat release and emission characteristics of a diesel engine are experimentally investigated. Initially, experimental studies are performed by consuming diesel fuel to obtain engine standard values. After that, experiments were repeated for DWI with fuel utilizationinto the cylinder at certain mass ratios. Experiment results are given in comparison with standard engine data as a reference.

2. Materials and methods

In the experiments, a single-cylinder, four-stroke, direct injection, water-cooled diesel engine with bowl-in-piston geometry was used. The technical properties of the test engine is given in Table 1.

Table 1
Specification of the test engine.

Engine type	Super star
Bore [mm]	108
Stroke [mm]	110
Cylinder number	1
Stroke volume [dm^3]	1
Power @2200 rpm, [kW]	13
Injection pressure, [bar]	175
Start of injection, [°CA, bTDC]	34
Maximum speed, [rpm]	2400
Cooling type	Water
Injection type	DI

During experiments, the engine was coupled to a 20 kW electric dynamometer. The power generated by the engine was determined with an S-type load cell with 0.01 kg sensitivity mounted to the torque arm. Engine fuel consumption was measured by volumetric method. Exhaust gas emission and opacity measurements were performed by Bosch-BEA 550 and BEA070 gas analysis equipments, respectively. Ambient temperature, cooling water inlet and outlet temperature, exhaust temperature, and oil temperature were measured by using NiCr-Ni type thermocouples during experiments. Air flow into the engine was determined by an air mass flow measurement system with control. The pressure measurement system was used to determine in-cylinder pressures in conjunction with a encoder of 0.1°CA sensitivity. An electronically controlled injection system was used to inject water into the engine cylinder with specified quantities and at start of injection angles. The injection system operates by collecting engine speed, top dead center (TDC) and crank angle position data from the engine continuously. Operating parameters of water injector were determined prior to experiments to identify the quantity of water to be injected precisely. In determining injector parameters, considering that water would be injected from the injector against high pressures formed in the combustion chamber, water injection quantities were determined under an 80 bar high-pressure environment in the combustion chamber. For this purpose, before experimental studies, water quantities injected with a certain pulse amplitude were determined for different voltage values using a separate injector test setup at a constant water pressure by changing injector voltage values (12–30 V) and injector on-off (pulse amplitude) times. Water was pressurized with a high-pressure pump and regulated with a pressure regulator to be constant at 100 bars. Injector operating voltage value and pulse amplitude were tested by electronically-controlled injector control unit connected to water injector. For each pulse amplitude at different operating voltage values under constant pressure, the quantities of water injected from the injector were determined by using a precision balance of 0.001 g sensitivity. The injection delay of the injector was found to be 0.7 ms with 20 Volt current. When voltage value decreases, injection delay increases. Cam shaft positon and speed information was entered to the electronic control unit via encoder while TDC (top dead center) information was entered via TDC sensor. The experimental setup is shown in Fig. 1.

Experiments were repetitively carried out at full load condition and 1200, 1400, 1600, 1800, 2000 and 2200 rpm engine speeds. Before recording data in the experiments, it was ensured that engine cooling water temperature and oil temperature values were stable. Experimental studies were continued progressively. First, engine standard values were determined by using diesel fuel. Fuel mass flow delivered to the engine was determined for each speed and then the fuel quantity injected for each cycle was calculated. Before the experiments with DWI, optimum start of injection angle was determined regarding engine effective power and NOx emissions. Therefore, water injection was done at different start of injection angles, while operating the engine at maximum torque, starting from the intake time top dead center (i-TDC) of the W50-water injection rate. The optimum start of water injection angle was found to be 270°CA for effective power and low

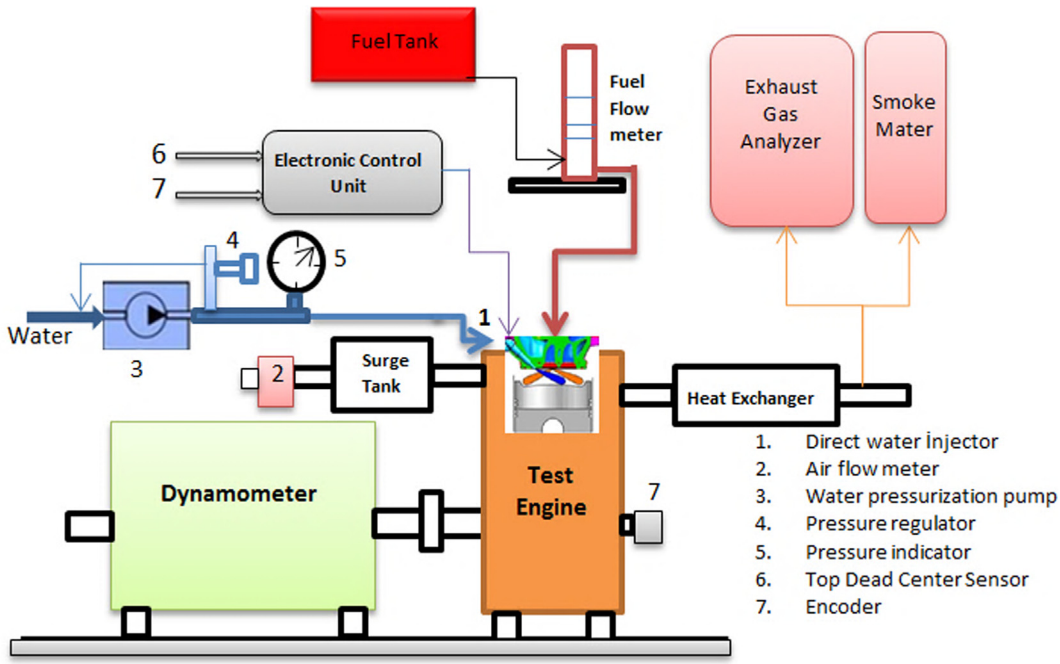

Fig. 1. Test setup.

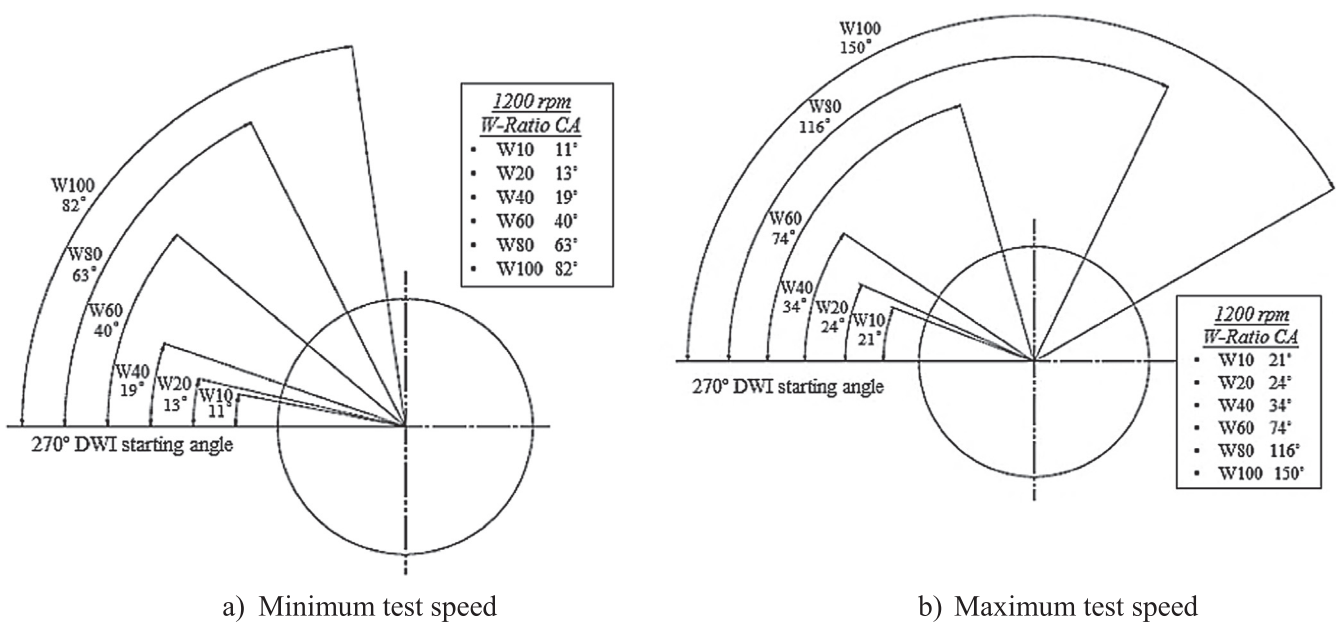

Fig. 2. Injection angle of DWI injector depending upon engine speed at different water injection rates.

Table 2
Engine test conditions with diesel and DWI.

Type	Value
Load	Full load condition
Engine speed, rpm	1200, 1400, 1600, 1800, 2000, 2200
Water starting of Injection, CA bTDC	270
Water injection pressure, bar	100
Water injection temperature, °C	20 (Ambient temperature)
Water injector voltage, V	20
Injection delay of the water injector, ms	0.7 (at 20 V)
Water injection duration, CA	11–150 for different water ratio
Water injector duration, ms	0.9-W20; 1.3-W40; 2.8-W60; 4.4-W80; 5.7-W100

NOx emissions. Afterwards, at this injection angle, experiments with DWI were performed for each engine speed at 10%, 20%, 40%, 60%, 80% and 100% (W100) of fuel injected to the cylinder by mass. Setting the voltage value applied to water injector and start of water injection angle, the injection was ensured to be finished within the combustion process regarding operation at maximum engine speed. Fig. 2 shows start of water injection angles at the minimum and maximum test speeds by indicating 270°CA start of water injection angle. Engine test conditions for standard engine and DWI application are given in Table 2.

The measurements were repeated 5 times for each test point and average data has been considered. All the total uncertainties of performance characteristics are calculated as described above. The accuracies and total uncertainties of characteristics calculated with

Table 3
The errors in parameters and total uncertainties.

Parameters	Systematic Errors, ±
Load, kg	0.1
Speed, rpm	1.0
Time, s	0.1
Temperature, °C	1.0
Fuel consumption, s	0.01
NO, ppm	5% of measured value
HC, ppm	5% of measured value
O_2	Vol.% 0.1
CO, %	Vol.% 0.03
CO_2, %	Vol.% 0.5
Smoke, %	1%
	Total uncertainty, %
Specific fuel consumption, g/kWh	1.5
Brake power, kW	1.3
Effective efficiency, %	1.5

respect to measured data are shown in Table 3.

Calculation of heat release rate: The first law of thermodynamics is applied to engine cylinder using a single zone combustion analysis. Rate of heat release analysis is used to determine the rate of fuel chemical energy released during combustion. Assumptions made for the heat release rate calculations are given in the following.

- For single zone model, heat release is calculated considering an average value for the cylinder volume.
- In-cylinder charge is in thermodynamic and chemical equilibrium.
- Fuel vapor and combustion products in cylinder obey the ideal gas law.
- Blow-by flows through the piston, piston rings and cylinder walls are disregarded.
- Throughout combustion process in cylinder charge temperature has a uniform temperature.
- Instantaneous convection heat transfer coefficient is calculated using Woschni correlation.

3. Results and discussion

Effect of start of water injection timing on NO and effective power: For the determination of the optimum start of injection angle for water to be delivered to the engine, the engine was operated at 1600 rpm, maximum torque speed, water injection was repeated at different injection angles starting from i-TDC until the injection angle, which made the performance maximum and NOx emissions minimum, was obtained. Fig. 3 shows changes in NOx and effective power with the start of water injection angle. The optimum start of injection angle was determined to be 270°CA in terms of NOx and effective power, corresponding to the middle of the compression stroke. All the rest of experiments with water injection were performed at this start of injection angle.

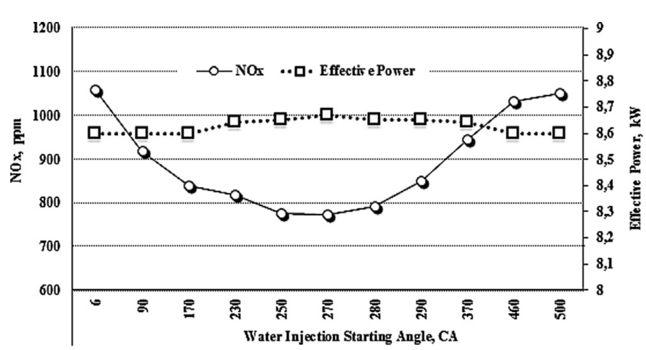

Fig. 3. Variation of effective Power and NOx emissions with DWI start of injection angle, (1600 rpm and W50).

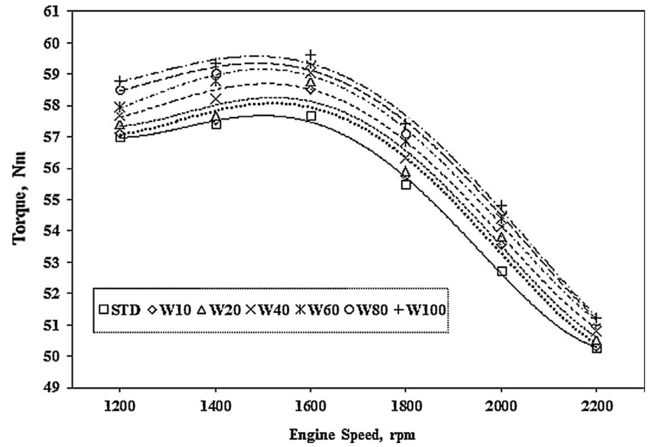

Fig. 4. Changes in torque depending on water injection quantity and engine speed.

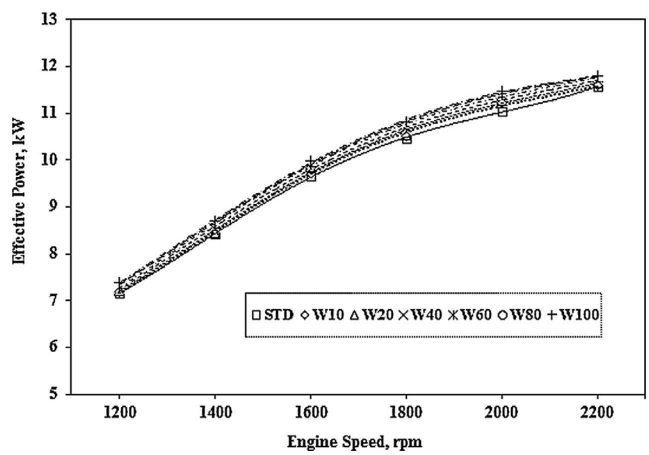

Fig. 5. Changes in effective power depending on water injection quantity and engine speed.

Figs. 4 and 5 show the changes in engine torque and effective power, respectively. It is clear from the figures that the engine torque reduces with increasing engine speed. However, the brake power increases with increasing engine speed up to 2200 rpm. In standard condition, the maximum torque was measured to be 57.7 Nm at 1600 rpm. When DWI was applied to the engine, increases were observed in torque values at all water ratios. The maximum increase was obtained at W100.

As seen in Fig. 5, when applying water injection to the engine, increases were obtained for the effective power at all engine speeds. Standard engine maximum effective power was measured 11.6 kW at 2200 rpm. When DWI was applied, the maximum increase in power (3.7%) was obtained at W100 (%100). Wang et al. [56] stated by reasoning water, having less surface tension compared to the fuel, caused micro-explosions in the cylinder during combustion, and thus the mixture formation is improved and combustion efficiency is increased. It can be concluded that DWI is one of the factors affecting the increases in torque and effective power. Moreover, when examining the in-cylinder pressure change shown in Fig. 12 that, in case of water delivery into the engine, in-cylinder pressures decreased due to heat removal of water and thus compression losses are decreased. Although in-cylinder maximum pressures are decreased by water injection due to the amount of decrease in compression was high, they increased compared to the on-line standard condition. It is considered that these effects cause increases in torque and effective power values of the engine. Possible effect of water injection on the increases in engine torque and effective

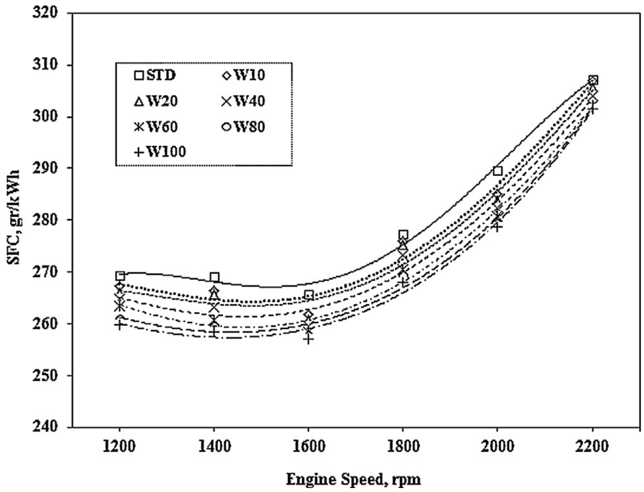

Fig. 6. Changes in SFC depending on water injected quantity and engine speed.

power can be explained as follows. Examining heat release rate curves in Fig. 14, ignition delay is increased by direct water injection into the engine and heat release rate is higher in the region beyond TDC. Heat release during the expansion stroke, results in increase in cycle work output, thus increase in power.

Fig. 6 shows the effects of DWI at the compression period on SFC of the engine. As can be seen from the figure that, decreases are observed in SFC at all water ratios. Maximum reduction in SFC occurred at W100 water injection ratio. Minimum SFC for standard engine was 265.7 g/kWh at 1600 rpm and for W100 water injection ratio at the same speed was 257.1 g/kWh. Maximum reduction was calculated as 4.1% at 1400 rpm at W100. Standard engine experiments and experiments using DWI are conducted at the same conditions. However, decrease in SFC by water injection is considered to be reasoning from the increase in engine effective power by water injection.

Fig. 7 shows comparatively the effects of DWI to the engine in different ratios on effective efficiency at full load condition.

At speeds where experiments were carried out, increases were obtained at the effective efficiency compared to the standard data at all water ratios injected. There were more increases in effective efficiency at lower engine speeds, while decreases were observed in the increase rate of efficiency with increasing engine speed. The maximum increase in effective efficiency was found to be 4% at 1400 rpm at W100 water injection ratio. Standard engine effective efficiency was calculated at 31.9% at 1600 rpm, while it was 32.9% at W100. Factors causing

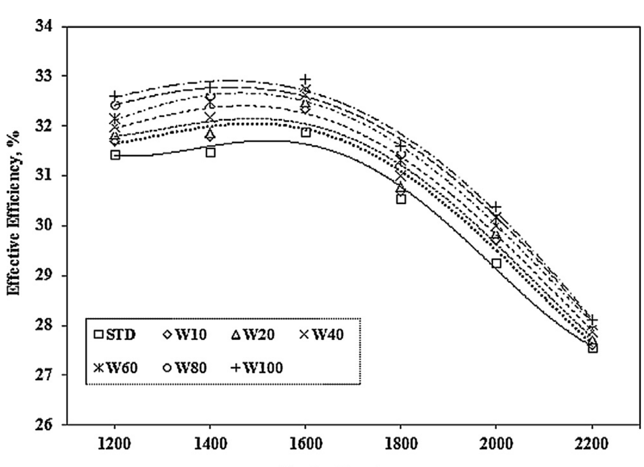

Fig. 7. Changes in effective efficiency depending on water injected quantity and engine speed.

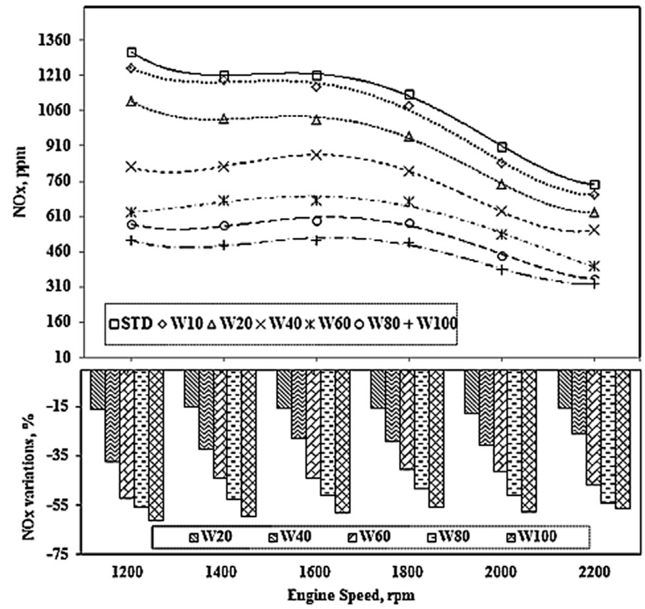

Fig. 8. Changes in NOx emissions depending on water injection quantity and engine speed.

decrease in SFC, increased effective efficiency.

Fig. 8 shows NOx emission changes at DWI in different ratios at full load condition. When DWI was applied to the engine, considerable decreases were recorded in NOx emissions compared to the standard value. Maximum decrease amount (61%) was obtained at W100. Decrease quantities according to different water ratios were measured as 16%, 37%, 52%, and 56% at W20, W40, W60 and W80, respectively. Standard engine maximum NOx value was 1313 ppm at 1200 rpm, while the maximum value was measured as 509 ppm at W100. Maximum reduction in NOx emission increased with increasing water ratio. In internal combustion engines, NOx emission reactions are highly affected by excess air factor and high temperatures formed after combustion [57,58]. Investigating NOx formation mechanisms, greater the air induced into the cylinder, greater the NOx formation takes place, due to the increase in reacting nitrogen amount [59]. However, with a very high air excess coefficient, the amount of NOx will decrease as the excess air entering the cylinder decreases during operation.

When DWI is applied to the engine at compression stroke, any change occurring in the volumetric efficiency and the change in NOx emissions is not due to excess air factor. In this case, the only factor causing a reduction in NOx emissions is high heat capacity of the water injected. Specific heat of water is four times higher than that of air. When injecting water to the cylinder at compression stroke, heat capacities of the mixture of combustion products increase compared to the standard condition, depending on their specific heats. Increases in the heat capacities of combustion products cause reduction engine in-cylinder maximum combustion temperature. Because the reduction in combustion maximum temperature slows down the formation of NOx emission, decreases were seen in NOx emission values released from the engine in case of water injection. Fig. 15 shows in-cylinder temperature changes calculated for the standard engine and water injection applied in different ratios. As can be clearly seen from the Fig. 15 that in case of water injection, in-cylinder temperatures decreased and this reduction increased with increasing injected water ratio.

Fig. 9 compares the smoke opacity released at full load condition in different DWI ratios with values measured at standard conditions.

In case of water injection, there were decreases in the smoke opacity at 1200 rpm while there were no significant changes at other engine speeds, but slight increases were observed. In diesel engines the prominent factor to influence smoke opacity is the excess air coefficient.

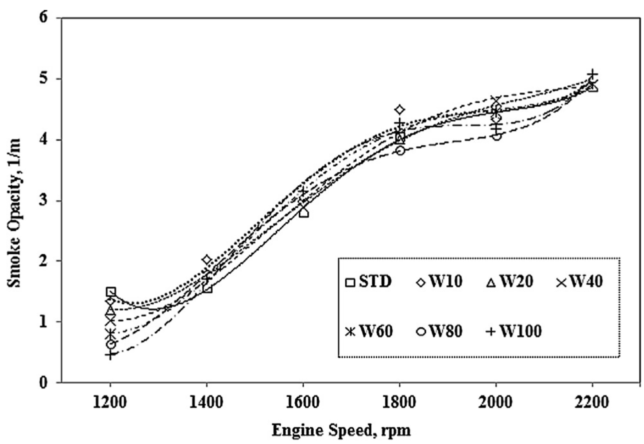

Fig. 9. Changes in smoke opacity depending on water injection quantity and engine speed.

And, excess air coefficient remains constant with DWI utilization. For smoke emissions state of fuel-air mixture in the cylinder is another important factor. The better the mixture formation, the lower the smoke opacity obtained. But, as a result of local rich regions in the cylinder and poor fuel–air mixture formation, smoke opacity increases. Slight improvement in mixture formation is expected by DWI, due to turbulence induced by the evaporation temperature of water. Therefore, increase in smoke emissions is not occurred by the reduction in cylinder temperatures. Moreover, at some speeds, reduction in smoke emissions is obtained compared to the standard data.

When water is injected to the engine in different ratios, comparison of HC emissions with those measured at standard conditions is shown in Fig. 10. Slight decreases were seen in HC emissions released from the engine in case of water injection at W10 and W20 ratios compared to standard condition while increases were determined at other water ratios. When water ratio in the cylinder increases, flame out near cool flame zones called cooling jackets is considered to be a possible reason. Among the most significant reasons to influence formation of HC emissions, is the flame quenching in the regions close to cylinder jacket. It is concluded that, with water injection into cylinder, resulting increase in the cooling effect of flame quenching regions, in-cylinder temperatures decrease and HC emissions increase.

Fig. 11 shows the comparison of CO emissions released in case of water injection in different ratios at full load condition with those measured at standard conditions. There was not a considerable change observed in CO emissions in case of water injection. Slight decreases were seen at lower engine speeds while there were slight increases observed at higher speeds.

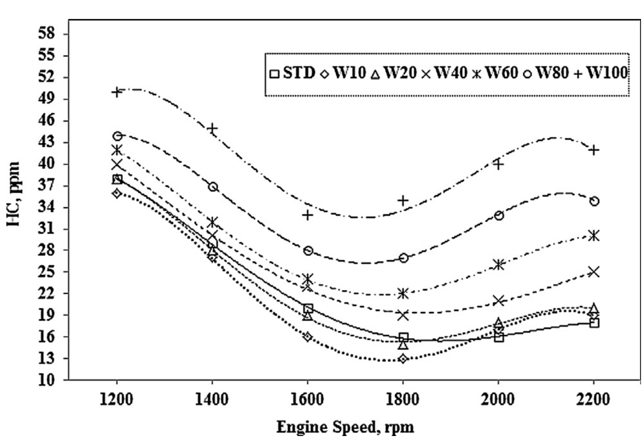

Fig. 10. Changes in HC emissions depending on water injection quantity and engine speed.

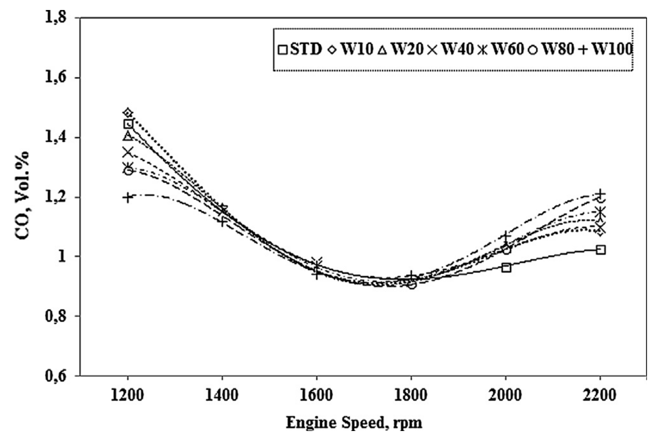

Fig. 11. Changes in CO emissions depending on water injection quantity and engine speed.

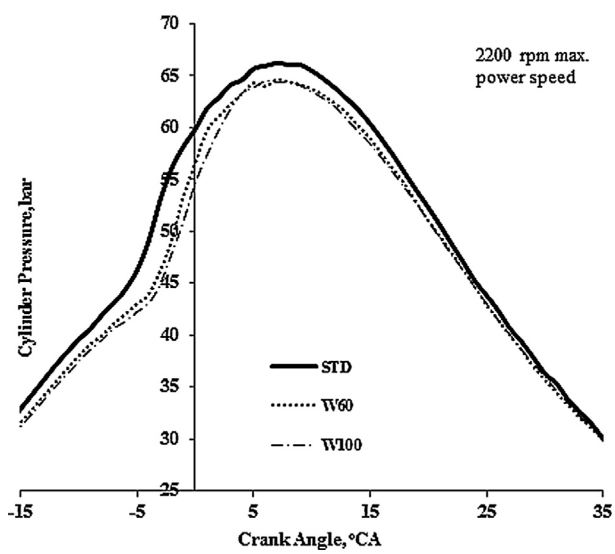

Fig. 12. Changes in cylinder pressure depending on water injection quantity and CA.

Fig. 12 shows pressure changes obtained in case of water injection to the engine in different ratios with respect to crank angle.

As seen from the figure, when applying water injection at compression period, pressures at compression stroke decreased due to heat removal by water. Slight decreases were observed in maximum pressure. Due to the decrease in pressure at the end of compression stroke by water injection and minor change in expansion pressure, negative work of the cycle decreased with water injection. On the other hand, motions due to vaporization of water improve air-fuel mixture formation. Thus, improvements were obtained with water injection in engine performance parameters.

Figs. 14–16 demonstrate cumulative heat release (%), heat release rate and in-cylinder temperature. When examining cumulative heat release changes are calculated in case of water injection with respect to the standard condition in Fig. 13, it is seen that water injection increases cumulative heat release. Start of combustion angle and burnt fuel mass percentages can be seen in Figure #. This curve represents normalized cumulative heat release. As seen in the figure, burnt fuel curve starts increasing just after the start of combustion and reaches to a maximum until close to half of the combustion duration. Later on, at a decreasing rate the curve reaches to unity as the combustion ends. Stages of combustion process can be derived by constructing the four characteristic parameters on curve. The parameters are start of combustion, flame formation duration taking place from the start of

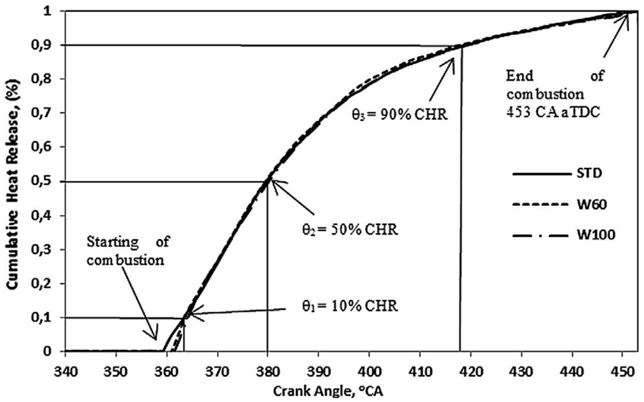

Fig. 13. Changes in cumulative heat release depending on water injection quantity and CA.

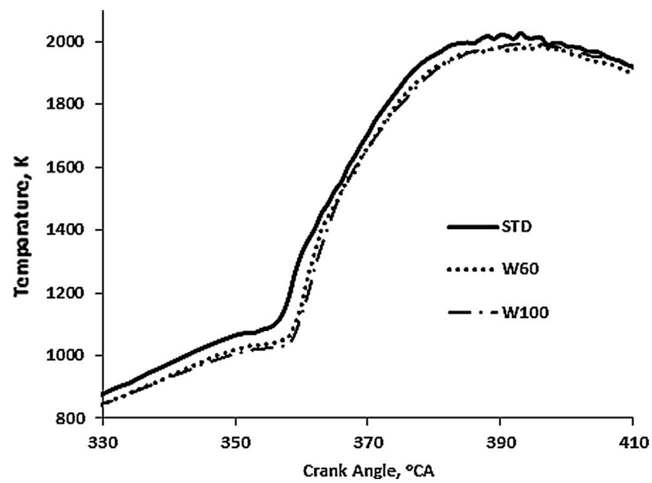

Fig. 15. Changes in cylinder temperature depending on water injection quantity and CA.

combustion until 10% burnt fuel fraction (θ_1), 50% burnt fuel fraction (θ_2), 90% burnt fuel fraction (θ_3), and the end of combustion, respectively. From the curve, start of combustion gets closer to TDC as ignition delay increases with DWI utilization. At 2200 rpm, measured ignition delay data are increased 0.0771 ms and 0.152 ms compared to standard data for W60 and W100, respectively. Ignition delays increase depending on water injection ratio. For 10% burnt fraction, situated after the ignition delay, differences compared to standard data are prevalent. However, 50% and 90% burnt fraction angles no significant changes are seen. Considering DWI cases, although the ignition delays increase, rapid combustion period (θ1–θ3) is the same as standard engine data. But, beyond 10% burnt fraction fuel combustion takes places faster compared to standard engine data. Therefore, effect of improvements in engine parameters using water injection can be observed. Using water injection compression work is reduced, and rapid combustion period, occurring after TDC, more heat release is observed.

Fig. 14 shows heat release rates obtained for the standard engine with water injection ratio. When examining graphs, it is seen that ignition delay extends due to water injection and time increases with increasing the injected quantity. In the graph obtained for standard condition, peak value of heat release rate is obtained for the fuel accumulated during ignition delay. It is released at the diffusion combustion phase. And after this value, heat release slightly decreases, reaches a maximum at 10°CA at the controlled combustion phase, and then decreases with expansion process. When applying water injection, there was not a significant change at W10 compared to standard data, while heat release rates differed at other water injection ratios. Water injected into the cylinder at compression stroke removes heat from the cylinder. This increases ignition delay time and causes the release of

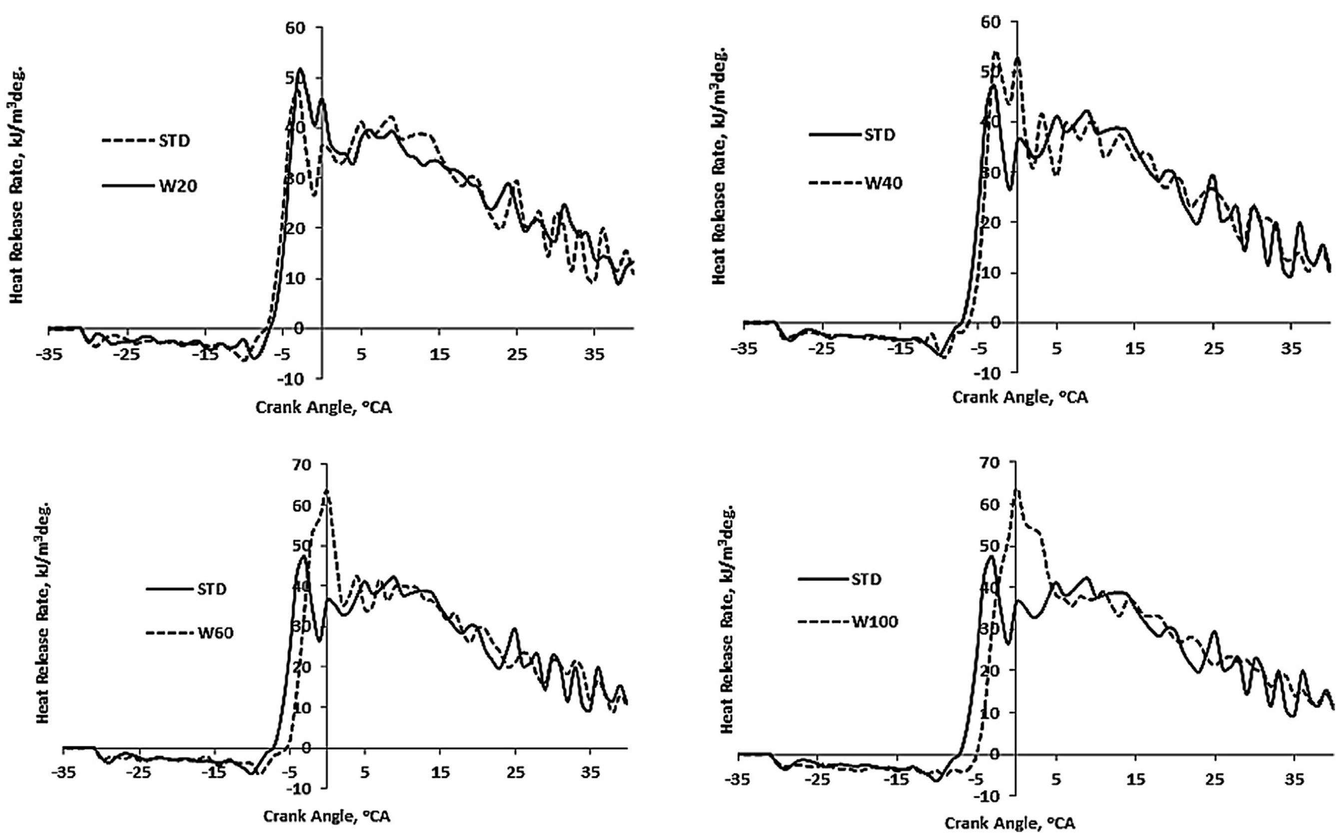

Fig. 14. Changes in heat release rate depending on water injection quantity and CA.

more energy after TDC at the diffusion combustion phase. Because all engine experiments were performed at constant fuel injection angle, it is understood that the noise level of the engine would slightly increase when applying water injection. The shift of heat release to TDC and thus change in combustion regime positively affected the performance.

Fig. 15 shows the in-cylinder temperatures for both the standard engine and DWI application in different ratios. When applying water injection to the engine, the in-cylinder temperature is observed to decrease. Because the heat capacity of the mixture increased with increasing water ratio, so the temperatures decreased. The decrease in in-cylinder temperatures causes considerable reductions in NOx emissions.

4. Conclusion

In this study, the effects of applying DWI to a diesel engine in different ratios on the engine performance, emission formation and combustion were experimentally investigated. Water was injected into the combustion chamber using a dedicated water injector placed on the cylinder head at different ratios by the electronically-controlled DWI system. The aim was to reduce NOx emissions with DWI, which is a major problem for diesel engines. The results of studyare ggiven in the following.

- The optimum start of injection start angle for DWI was determined to be 270°CA at compression stroke.
- Using DWI, there were increases in engine torque, effective power and effective efficiency at all water ratios and maximum increase ratios were obtained at W100. Engine torque and effective power increased by 3.7%, effective efficiency increased by 4% and SFC decreased by 4.1%.
- Reductions by 61% were achieved in NOx emissions.
- Smoke opacity decreased at 1200 rpm in case of water injection while there were slight increases in other engine speeds.
- Slight decreases were seen in HC emission at W10 and W20 ratios, while there were increases at other water ratios.
- There was not a considerable change observed in CO emissions with DWI. At low engine speeds, slight decreases were seen while CO emissions increased at high speeds.
- It was observed that in-cylinder pressure values decreased by DWI at compression stroke and compression work decreased. Peak pressure values slightly decreased while there was not an apparent change in expansion stroke pressure values.
- Cumulative heat release increased by water injection.
- It was determined that ignition delay increased with increasing water ratio and combustion regime changed.
- It was seen that the maximum values of heat release shifted to TDC depending on water ratio and the direction of conventional diesel heat release curve changed. It is seen that the heat release curve obtained with ignition delay increase and the changes formed in the combustion process resembled to homogeneous charged study model.
- In accordance with the results obtained from the study, it is seen that DWI is an advantageous method over many conventional methods used to reduce NOx emissions.
- The optimum DWI ratio was determined as W60 regarding performance parameters, NOx and HC emissions.

Acknowledgement

This work has been supported by the Sakarya University of Applied Sciences – Turkey Scientific Research Projects Coordinator with the project numbers of 2018-2-7-2.

References

[1] Zhaowen W, Shuguo S, Sheng H, Jie T, Tao D, Xiaobei C, et al. Effects of water content on evaporation and combustion characteristics of water emulsified diesel spray. Appl Energy 2018;226:397–407.
[2] Ismael Mhadi A, Heikal Morgan R, Aziz A Rashid A, Syah Firman, Crua Cyril. The effect of fuel injection equipment on the dispersed phase of water-in diesel emulsions. Appl Energy 2018;222:762–71.
[3] Elsanusi Osama Ahmed, Roy Murari Mohon, Sidhu Manpreet Singh. Experimental investigation on a diesel engine fueled by diesel-biodiesel blends and their emulsions at various engine operating conditions. Appl Energy 2017;203:582–93.
[4] Kannan GR, Karvembu R, Anand R. Effect of metal based additive on performance emission and combustion characteristics of diesel engine fuelled with biodiesel. Appl Energy 2011;88:3694–703.
[5] Hwang J, Bae C, Patel C, Agarwal RA, Gupta T, Kumar Agarwal A. Investigations on air-fuel mixing and flame characteristics of biodiesel fuels for diesel engine application. Appl Energy 2017;206:1203–13.
[6] Jiaqiang E, Pham M, Zhao D, Deng Y, Le D, Zuo W, et al. Effect of different Technologies on combustion and emissions of the diesel engine fueled with biodiesel: a review. Renew Sustain Energy Rev 2017;80:620–47.
[7] Musculus MPB, Miles PC, Pickett LM. Conceptual models for partially premixed lowtemperature diesel combustion. Prog Energy Combust Sci 2013;39:246–83.
[8] Noh HK, No S-Y. Effect of bioethanol on combustion and emissions in advanced CI engines: HCCI, PPC and GCI mode – a review. Appl Energy 2017;208:782–802.
[9] Roy S, Hegde MS, Madras G. Catalysis for NOx abatement. Appl Energy 2009;86:2283–97.
[10] Jiang J, Li D. Theoretical analysis and experimental confirmation of exhaust temperature control for diesel vehicle NOx emissions reduction. Appl Energy 2016;174:232–44.
[11] Park SH, Yoon SH. Injection strategy for simultaneous reduction of NOx and soot emissions using two-stage injection in DME fueled engine. Appl Energy 2015;143:262–70. https://doi.org/10.1016/j.apenergy.2015.01.049.
[12] Höök M, Tang X. Depletion of fossil fuels and anthropogenic climate change—a review. Energy Pol 2013;52:797–809.
[13] Mahrous A-FM, Potrzebowski A, Wyszynski ML, Xu HM, Tsolakis A, Luszcz P. A modelling study into the effects of variable valve timingon the gas exchange process and performance of a 4-valve DI homogeneouscharge compression ignition (HCCI) engine. Energy Convers Manage 2009;50:393–8.
[14] Nora Macklini Dalla, Lanzanova Thompson Diórdinis Metzka, Zhao Hua. Effects of valve timing, valve lift and exhaust backpressureon performance and gas exchanging of a two-stroke GDIengine with overhead valves. Energy Convers Manage 2016;123:71–83.
[15] Ayhan V, Tunca S. Experimental investigation on using emulsified fuels with different biofuel additives in a DI diesel engine for performance and emissions. Appl Therm Eng 2018;129:841–54.
[16] Wicka Maximilian, Bedeia Julian, Gordonb David, Woutersc Christian, Lehrheuerc Bastian, Nussd Eugen, et al. In-cycle control for stabilization of homogeneous charge compression ignition combustion using direct water injection. Appl Energy 2019;240:1061–74.
[17] An H, Yang WM, Chou SK, Chua KJ. Combustion and emissions characteristics of diesel engine fueled by biodiesel at partial load conditions. Appl Energy 2012;99:363–71.
[18] Ma Y, Huang S, Huang R, Zhang Y, Xu S. Ignition and combustion characteristics of n-pentanol–diesel blends in a constant volume chamber. Appl Energy 2017;185:519–30. https://doi.org/10.1016/j.apenergy.2016.11.002.
[19] Lapuerta M, Armas O, Rodríguez-Fernández J. Effect of biodiesel fuels on diesel engine emissions. Prog Energy Combust Sci 2008;34:198–223.
[20] Hulwan DB, Joshi SV. Performance, emission and combustion characteristic of a multicylinder DI diesel engine running on diesel–ethanol–biodiesel blends of high ethanol content. Appl Energy 2011;88:5042–55.
[21] Parlak A, Ayhan V, Cesur I, Kökkülünk G. Investigation of the effects of steam injection on performance and emissions of a diesel engine fuelled with tobacco seed oil methyl ester. Fuel Process Technol 2013;116:101–9.
[22] Lin CY, Chen LW. Comparison of fuel properties and emission characteristics of two and three-phase emulsions prepared by ultrasonically vibrating and mechanically homogenizing emulsification methods. Fuel 2008;87(10–11):2154–61. https://doi.org/10.1016/j.fuel.2007.12.017.
[23] Attia AMA, Kulchitskiy AR. Influence of the structure of water-in-fuel emulsion on diesel engine performance. Fuel 2014;116:703–8. https://doi.org/10.1016/j.fuel.2013.08.057.
[24] Ismael MA, Heikal MR, Rashid A, Aziz A, Crua C. An overview of experimental techniques of the investigation of water-diesel emulsion characteristics droplets micro-explosion. ARPN J Eng Appl Sci 2016;11(20).
[25] Ayhan V. Effects of emulsified fuel on the performance and emission of direct injection diesel engine. J Energy Eng 2013;139:91–8.
[26] Mello JP, Mellor AM. NOx emissions from direct injection diesel engines with water/steam dilution. SAE paper 1999-01-0836; 1999.
[27] Fahd MEA, Wenming Y, Lee PS, Chou SK, Yap CR. Experimental investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition. Appl Energy 2013;102:1042–9. https://doi.org/10.1016/j.apenergy.2012.06.041.
[28] Yang WM, et al. Impact of emulsion fuel with nano-organic additives on the performance of diesel engine. Appl Energy 2013;112:1206–12. https://doi.org/10.1016/j.apenergy.2013.02.027.
[29] Elsanusi OA, Roy MM, Sidhu MS. Experimental investigation on a diesel engine fueled by diesel-biodiesel blends and their emulsions at various engine operating conditions. Appl Energy 2017;203:582–93. https://doi.org/10.1016/j.apenergy.2017.06.052.
[30] Guo Z, Wang S, Wang X. Stability mechanism investigation of emulsion fuels from

biomass pyrolysis oil and diesel. Energy 2014;66:250–5. https://doi.org/10.1016/j.energy.2014. 01.010.

[31] Feng L, Du B, Tian J, Long W, Tang B. Combustion performance and emission characteristics of a diesel engine using a water-emulsified heavy fuel oil and light diesel blend. Energies 2015;8(12):13628–40. https://doi.org/10.3390/en81212387.

[32] Ithnin AM, Ahmad MA, Bakar MAA, Rajoo S, Yahya WJ. Combustion performance and emission analysis of diesel engine fuelled with water-in-diesel emulsion fuel made from low-grade diesel fuel. Energy Convers Manage 2015;90:375–82.

[33] Mazlan NA, et al. Effects of different water percentages in non-surfactant emulsion fuel on performance and exhaust emissions of a light-duty truck. J Clean Prod 2018;179:559–66. https://doi.org/10.1016/j.jclepro.2018.01.143.

[34] Lif A, Holmberg K. Water-in-diesel emulsions and related sytems. Adv Incolloid Interf Sci 2006:231–9.

[35] Nadeem M, Rangkuti C, Anuar K, Haq MRU, Tan IB, Shah SS. Diesel engine performance and emission evaluation using emulsified fuels stabilized by conventional and gemini surfactants. Fuel 2006;85(14–15):2111–9. https://doi.org/10.1016/J.FUEL.2006.03.013.

[36] Lin C-Y, Chen L-W. Emulsification characteristics of three- and two-phase emulsions prepared by the ultrasonic emulsification method. Fuel Process Technol 2006;87:309–17.

[37] Armas O, Ballesteros R, Martos FJJ, Agudelo JRR. Characterization of light duty Diesel engine pollutant emissions using water-emulsified fuel. Fuel 2005;84(7–8):1011–8.

[38] Noor El-Din MR, El-Hamouly SH, Mohamed HM, Mishrif MR, Ragab AM. Water-indiesel fuel nanoemulsions: preparation, stability and physical properties. Egypt J Pet 2013;22:517–30.

[39] Ma X, Zhang F, Han K, Zhu Z, Liu Y. Effects of intake manifold water injection on combustion and emissions of diesel engine. Energy Proc 2014;61:777–81.

[40] Hountalas DT, Mavropoulos GC, Zannis TC, Mamalis SD. Use of water emulsion and intake water injection as NOx reduction techniques for heavy duty diesel engines. SAE Int 2006.

[41] Arabaci E, İçingür Y, Solmaz H, Uyumaz A, Yilmaz E. Experimental investigation of the effects of direct water injection parameters on engine performance in a sixstroke engine. Energy Convers Manage 2015;98:89–97. https://doi.org/10.1016/J.ENCONMAN.2015.03.045.

[42] Sarvia A, Kilpinenb P, Zevenhovena R. Emissions from large-scale medium-speed diesel engines: 3.Influence of direct water injection and common rail. Fuel Process Technol 2009:222–31.

[43] Zhang Z, Kang Z, Jiang L, Chao Y, Deng J, Hu Z, et al. Effect of direct water injection during compression stroke on thermal efficiency optimization of common rail diesel engine. Energy Proc 2017;142:1251–8.

[44] Bedford F, Rutland C, Dittrich P, Wirbeleit F. Effects of direct water injection on Dİ diesel engine combustion. SAE Pap 2000;01–2938.

[45] Selim MYE, Elfeky SMS. Effects of diesel/water emulsion on heat flow and thermal loading in a pre-combustion chamber diesel engine. Appl Therm Eng 2001;21(15):1565–82.

[46] Duffy KP, Mellor AM. Further developments on a characteristic time model for NOx emissions from diesel engines. SAE paper 982460; 1998.

[47] Lif A, Skoglundh M, Gjirja S, Denbratt I. Reduction of soot emissions from a direct injection diesel engine using water-in-diesel emulsion and microemulsion fuels. SAE Int 2007.

[48] Christensen M, Johansson B. Homogeneous charge compression ignition with water injection. SAE paper 1999-01-0182; 1999.

[49] Psota MA, Easley WL, Fort TH, Mellor AM. Water injection effects on NOx emissions for engines utilizing diffusion flame combustion. SAE Trans J Engines 1997;106:1835–43. [SAE 971657, Section 3].

[50] Abu-Zaid M. Performance of single cylinder, direct injection Diesel engine using water fuel emulsions. Energy Convers Manage 2004;45(5):697–705. https://doi.org/10.1016/S0196-8904(03)00179-1.

[51] Shinjo JX, Ganippa LC, Megaritis A. Physics of puffing and microexplosion of emulsion fuel droplets. Phys Fluids 2014.

[52] Breda K. Influence of biodiesel on engine combustion and emission characteristics. Appl Energy 2011;88:1803–12.

[53] Leng L, Yuan X, Zeng G, Wang H, Huang H, Chen X. The comparison of oxidative thermokinetics between emulsion and microemulsion diesel fuel. Energy Convers Manage 2015;101:364–70.

[54] Şahin Z, Tuti M, Durgun O. Experimental investigation of the effects of water adding to the intake air on the engine performance and exhaust emissions in a DI automotive diesel engine. Fuel 2014;115:884–95.

[55] Mingrui W, Sa NT, Turkson RF, Jinping L, Guanlun G. Water injection for higher engine performance and lower emissions. J Energy Inst 2017;90:285–99.

[56] Shah S, Maiboom A, Tauzia X, Hétet J. Experimental study of inlet manifold water injection on a common rail HSDI automobile diesel engine, compared to EGR with respect to PM and NOx emissions and specific consumption. SAE Technical Paper (2009) 01-1439; 2009. doi: 10.4271/2009-01-1439.

[57] Gonca G. Investigation of the effects of steam injection on performance and NO emissions of a diesel engine running with ethanolediesel blend. Energy Convers Manag 2014;77:450–7.

[58] Ayhan V. Investigation of the effects of steam injection into the diesel engine on NOx and PM emissions, Sakarya University, Institute of Science and Technology Phd thesis, Sakarya, Turkey; 2009.

[59] Ayhan V, Çangal Ç, Cesur İ, Çoban A, Ergen G, Çay Y, et al. Optimization of the factors affecting performance and emissions in a diesel engine using biodiesel and EGR with Taguchi method. Fuel 2020;261:116371.