Experimental investigation of a diesel engine power, torque and noise emission using water-diesel emulsions

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Abstract

In the present study, the results of an investigation on a Perkins A63544 direct injection diesel engine using water-diesel emulsions (2, 5, 8 and 10% by volume of water) are reported. The engine was run at different engine speeds ranging from 1400 to 1900 rpm for power and torque analysis with steps of 100 rpm. In order to evaluate noise emissions, four engine speeds (1600 to 1900 rpm with steps of 100 rpm) and four engine loading conditions (25, 50, 75 and 100%) were selected. No change in engine components and systems was made. Two factors completely randomized design was used for statistical analysis of the effects of engine speeds and fuel blends on the engine power and torque. According to the analysis of variance, engine speeds and fuel types had statistically significant effects at 1% probability level ($P < 0.01$) on the average values of the engine power and torque. Adding water to neat diesel fuel, was beneficial to increase engine power and torque significantly due to combustion efficiency improvement, but the lower calorific value of the emulsion reduced engine power and torque at higher water concentrations. The presence of water in neat diesel fuel generally increased ignition delay and engine noise emissions. Emulsion combustion at higher speeds didn't show higher sound pressure levels than neat diesel, which may be due to the decrease in heat release rate during combustion process. The 2% water-diesel emulsion increased power and torque output significantly without increasing engine noise emission. So, it showed a good potential to be considered as an appropriate alternative to neat diesel fuel.

Keywords

Water-Diesel emulsions; engine noise emission; engine power; engine torque.

Nomenclature	PTO power take-off
NIOSH the United States National Institute for Occupational Safety and Health	FFT Fast Fourier Transform P engine sound pressure (Pa)
DI direct injection	p_{rms} root mean square sound pressure (Pa)
PM Particulate Matter	p_{cool} Cool Edit sound pressure
MF Massy Ferguson	LA overall sound pressure level (dB(A))
E_0 neat diesel fuel	L_p sound pressure level (dB(A))
E_2 2% water and 98% diesel	p_0 reference pressure (20×10^{-6} Pa)
E_5 5% water and 95% diesel E_8 8% water and 92% diesel E_{10} 10% water and 90% diesel	L_{pi} sound pressure levels at band-center frequencies of 1/3rd octave frequency band (dB(A))
HRR heat release rate	τ time interval of measurement
UHC Unburend Hydro Carbon	NO_x nitrogen oxides
ANOVA analysis of variance	

1. Introduction

Diesel engines are efficient and economic power sources that are widely used in several industries. However, their noise is louder than spark ignition ones and it may be, in some cases, a big concern in many applications [1]. Previous research studies showed that human beings are affected mentally, physically and socially by excessive noise levels [1-3]. In account of the excessive noise threats on humans, NIOSH developed regulations in order to restrict the duration of human noise exposure. It defined exposure to a 85 dB(A) noise level for 8-hour/day or exposure to 88 dB(A) noise level for 4-hour/day as one noise dose [4]. Humans could be exposed to more than one noise dose per day and it was recommended to reduce noise levels below 80 dB(A), although some countries are promoting noise reduction and control programs to lower noise levels below 75 dB(A) [1].

In diesel-powered vehicles and equipments, the engine is the main source of noise [5-6]. For that reason, researchers have devoted significant efforts to mitigate diesel engine noise. The combustion noise was the main part of the diesel engine noise [7]. Ghaffarpour and Noorpoor [8] used split injection technique in automotive DI diesel engines to control combustion noise by directly acting on the source. Combustion noise may also be affected by the type of fuel. Nguyen and Mikami [9] found a decrease in combustion noise at late diesel fuel injection timings with 10% vol. hydrogen addition to the intake air. Transient performance of a diesel engine and the overall combustion noise radiation was evaluated using bio-fuels and minor effects were reported [10].

The stringency of international regulations on exhaust emissions are pushing researchers to investigate alternative fuels to reduce their pollution. In the last two decades, water-diesel emulsions have been studied with the aim of to solving the ‘‘PM-NOx trade-off’’ [11, 12]. The results of those investigations also revealed that water-diesel emulsions could be used in diesel engines without changing pumps and injectors [13]. Recently, two comprehensive reviews were published about the application of emulsions and water in diesel emulsion [14, 15].

Debnath et al. [14] concluded that surfactans or surface reacting agents are needed for emulsion preparation and for having a good emulsion for diesel engine, the agent should have low Hydrophilic/Lipophilic Balance value. SPAN 80 and TWEN 20 with the quantity range from 0.2 to 5% (by vol.) are commonly used for emulsion prparation. They also reported that ultrasonic agitator yielded more stable emulsion than menchanical mixer. Emulsion spray has a little higher penetration than diesel. According to ithnin et al. [15] the majority of the studies reported thermal efficiency increment and combusion efficiency improvement using water in diesel emulsion. Generally there were no improvement in brake power, torque and specific fuel consumption when the total amount of diesel fuel in the emulsion is compared with that of the neat diesel fuel. Emulsion combustion increased UHC and CO and decreased NO_x and particulate matters.

A mixture of two or more normally immiscible liquids is defined as an emulsion. Sufficient stirring of the liquids in presence of an emulsifying agent is necessary to produce a stable emulsion. Chemical reaction rates can be enhanced by using the high power ultrasonic technique [16]. The ultrasonic irradiation to a solution periodically forms cavitation bubbles. Those bubbles grow and collapse impulsively during the adiabatic compression. These phenomena result in formation of hotspots, high speed micro-jets, micro-streaming and generation of a shockwave. Therefore, the ultrasonic technique can be used to prepare water-diesel emulsions [17–20].

Using water-diesel emulsions in diesel engine could cause additional momentum on the injection jet and consequently an improved mixing of fuel, air and tiny water particles. Furthermore, additional momentum leads to micro explosions, which further enhance fuel atomization [21].

Investigation of engine performance using water-diesel emulsions showed comparable torque, power and thermal efficiency for 5% and 10% water-diesel emulsions [22]. The results of a study revealed that the water-diesel emulsion produces less output power as compared to neat diesel fuel. However, at higher engine load, the engine efficiency obtained using the 10% water-diesel emulsion is comparable to that using neat diesel fuel [13]. The calorific value of water-diesel emulsions with a high percentage of water is much lower than with neat diesel, thus releasing a smaller amount of heat in the cylinders, with the consequence of a smaller power output [23].

The experimental results indicated that the ignition delay increases by using water-diesel emulsions [24–26]. The vaporization of water releases its latent heat and slows down the gradient of temperature in the droplet (physical delay) and, at the same time, reduces the fuel concentration (chemical delay) [26]. The increase of 0.2 ms in ignition delay was reported for water-diesel emulsion compared to neat diesel fuel [27]. As ignition delay increases, more time is available for evaporation and mixing and more fuel is burnt during the combustion process, which leads to an increase in the rate of heat release. Enhancing the reaction rate of diesel fuel improves combustion efficiency [22, 27, 28].

Simpler and less sophisticated diesel engines are widely used in mass transportation, heavy industries and especially agricultural sectors because they offer better fuel to power conversion efficiency than spark ignition types. But unfortunately most of the diesel engines for those applications are not of the newest technology, even though they are one of the major pollution contributors (especially NO_x) to present time. Water in diesel emulsion usage spreads around the world to decrease diesel engine pollution without needing to engine modifications. Studying the effect of emulsions in those engine technologies is important since it may represent a low cost method to improve emissions in them. Also, in many cases (especially in agricultural practices), human activity near diesel engine is needed for a long period of time. So, regarding to high noise and exhaust emission of these types of diesel engines, harmful impact of their noise effect on human beings (mentally, physically and socially) is so worrying.

But there is to limited information concerning noise emission of a DI diesel engine using water-diesel emulsions at part loads and varying engine speed. From this motivation the aim of this study was to investigate a MF 399 tractor engine power, torque and noise emission at different engine loads and speeds, without any modification in engine systems and using different percentages of water in emulsions.

2. Materials and methods

The neat diesel used in this study was purchased from a gas station in Tehran, Iran. Its characteristics were depicted in Table 1. A 400 W, 20 kHz horn-type piezoelectric ultrasonic transducer (UP400S made by Hielscher Ultrasonics GmbH) was used for the emulsification process. 2% vol. Span 80 (Sorbitane monooleate) was added into the diesel fuel-water mixture solution in order to improve its stability. The water-diesel fuel emulsions were 2% water and 98% diesel (E_2), 5% water and 95% diesel (E_5), 8% water and 92% diesel (E_8) and 10% water and 90% diesel (E_{10}). The important specifications of the emulsions such as density, kinematic and dynamic viscosity and pour point were measured.

Table 1. Neat diesel fuel characteristics

Properties	Unit	Neat Diesel
Calorific value	MJ/kg	42.75
Pour point	ºC	−12
Flash point	ºC	58
Cloud point	ºC	−4
Density @ 15 ºC	Kg/L	0.841
Cetane number	---	51.3
Sulphur	wt%	0.7

Ash	wt%	0.008
Kin viscosity at 40 ºC	cSt	3.1
Ramsbottom carbon residue	wt%	0.06

The schematic diagram of the engine testing setup is shown in Fig. 1. The power, torque and speed of a MF-399 tractor engine were measured by an eddy current dynamometer (NJ-FROMENT Σ5model, ±0.1 kW accuracy for power measurement, ±0.1 Nm accuracy for torque measurement and rotational speed measurement accuracy of ±1 rpm). The specifications of the tractor engine used to carry out the tests were depicted in Table 2. The engine warmed up before the experiments. The dynamometer was connected to PTO shaft of the tractor through special coupling. The tractor engine power, torque and noise emissions were measured using water-diesel emulsions at four different load conditions (25%, 50%, 75% and 100% load) and at six different engine speeds from 1400 rpm to 1900 rpm.

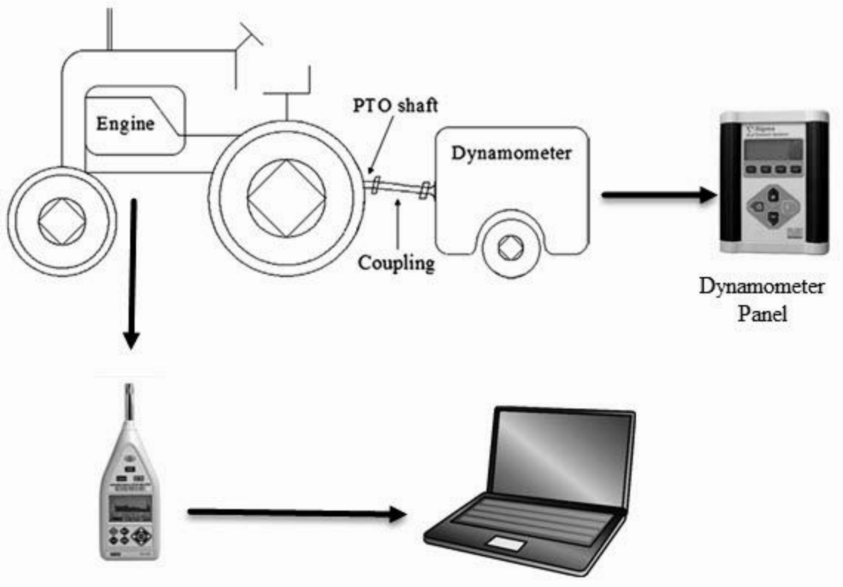


Fig. 1. Engine testing setup

Table 2. Perkins A63544 DI diesel engine specifications

Manufacture	Iran tractor manufacture CO
Combustion system	direct injection
Number of cylinder	6
Compression ratio	16:1
Bore × stroke	98.6 × 127
Cylinder volume	5.8 L
Maximum power at 2300 rpm	110 hp (82 kW)
Maximum torque at 1300 rpm	376 N m

A sound measurement test site was prepared and maintained according to SAE J1074 sound measurement standard [29]. To verify the data of sound level meter, they were compared with A-weighted overall sound pressure levels. So, engine sound pressure in time domain was recorded with Cool Edit Pro software. For correct conversion of analog signals to digital ones, data sampling rate must be at least two times of maximum frequency according to Nyquist criteria [30]. Human audible frequency ranges from 20 to 20000 Hz, so the sampling rate of software has been set at 48000 Hz. The duration of measurements was 10 seconds with three replications, so for each measurements the mean of 480000 samples were obtained.

The test area consisted of a flat open space free from obstacles and the effect of signboards, buildings and hillsides for at least 15 m from longitudinal center line of tractor and dynamometer. The wind speed was 11 km/h which satisfied standard recommendation. The background noise was 68.1 dB(A) (Fig. 2), so it can be neglected. A schematic diagram of the test area was shown in Fig. 3. The detailed specifications of the instruments for sound measurement were given in Table 3.

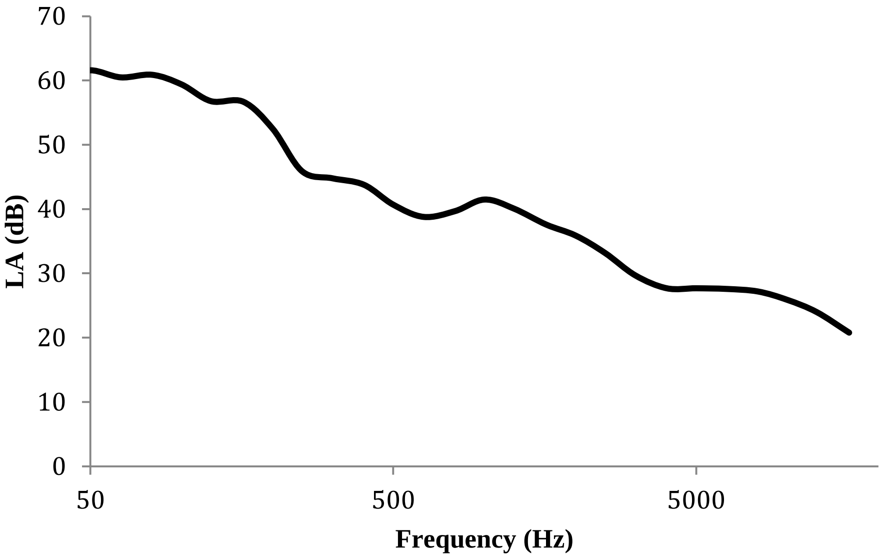


Fig 2. 1/3rd octave band frequency domain signal of background noise

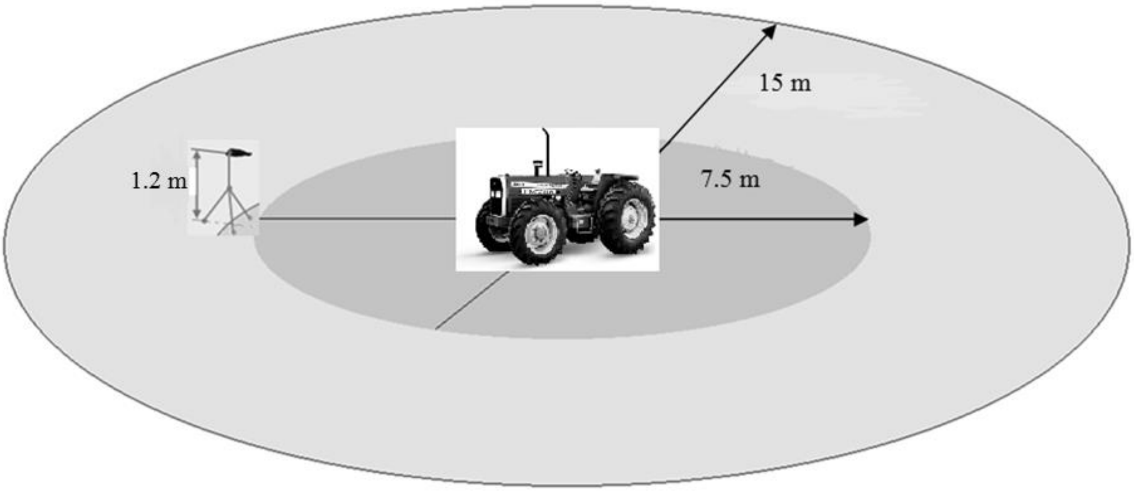


Fig. 3. A schematic diagram of the experimental setup

Table 3. Specifications of the instruments

Name of the instrument	Model	Accuracy/ Resolution	Range/Capacity	Sensitivity
Prepolarized condenser microphone	-	-	10 Hz-20 KHz	50 mV Pa^{-1}
Sound level meter	HT 157- class 1-Italy	0.1 dB	24-140 dB	-

Cup anemometer	Lutron AM-4220	0.1 m/s	0.9- 35 m/s	-
Digital thermometer	Testo Germany	0.1 ºC	-10 to 50 ºC	-

The HT 157 sound level meter calibration processes were done with its calibrator before and after data gathering. The calibrator signal was 94 dB with 1 kHz frequency which was shown in Fig. ..... The smae graph was obtained before and after measurements. According to the manual of sound level meter, the calibrator sound pressure is equal to 1 Pascal. So for having sound pressure signal of the engine and regarding to Fig. 4., the values of the software:

$$p = \frac{P_{\mathrm{cool}}}{610 \times 0.707} \qquad (1)$$

The measurements were done in linear scale but according to the standard and as the A-scale is widely used as a single measurement of possible hearing damage, annoyance caused by noise, and compliance with various noise regulations, sound pressure levels were converted to A-weighting using suitable filter.

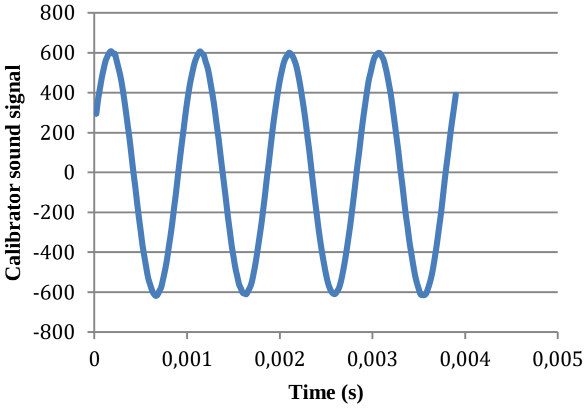


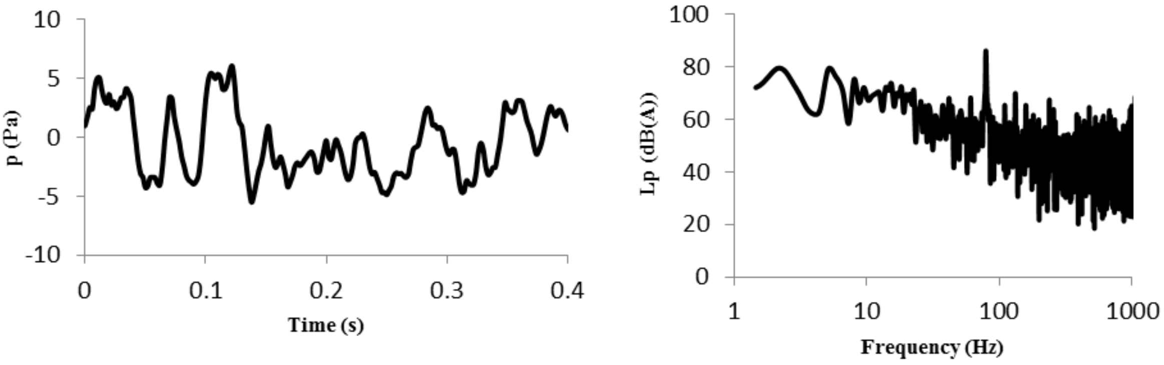
Fig. 4. Calibrator signal in time domain

The obtained signal in time domain could not reveal much information (Fig. 2). Therefore, the recorded digital data in time domain, p, were converted to frequency domain using a developed FFT computer program and the narrow (Fig. 5) and 1/3rd octave band frequency sound pressure levels were obtained. Due to un-smoothed nature of narrow and 1/3rd band frequency curves, comparing the data for different conditions is not so easy. So LA were derived from 1/3rd band signal in frequency domain using these equations [31]:

$$p_{rms} = \sqrt{\frac{\int_0^{\tau} p^2 dt}{\int_0^{\tau} dt}}$$

$$L_P = 10 \log \left(\frac{p_{rms}^2}{p_0^2} \right)$$

$$\mathrm{LA} = 10 \log \left(\sum_{i=1}^{n} 10^{L_{pi}/10} \right) \tag{2}$$



(a)

(b)

Fig. 5. (a) Time domain engine sound pressure and (b) Narrow band frequency domain signal of engine using E_{10} at full load condition.

The effects of engine speeds and fuel blend types (independent variables) on the engine power, torque and noise emission (dependent variables) were analyzed using the two factors completely randomized design.

Furthermore, the Duncan's multiple range test was used to evaluate the significant difference between the mean values of measured engine power and torque with the change in engine speed and fuel blend type. For evaluating noise emissions, in addition to engine speeds and fuel blend types, the effect of engine loading condition was studied too. Common letters were used when no significant difference at 1% probability level was found between the mean values.

3. Results and discussion

3.1. Emulsions specifications

The kinematic viscosity, dynamic viscosity, pour point and specific gravity of the fuel blends of the different emulsion types and neat petro-diesel were given in Table 4. As presented in this table, the kinematic viscosity, dynamic viscosity and density of the blends increased with increasing water percentage in emulsions. Similar results for viscosity [32, 33] and density [34] were reported in other studies. The presence of water in diesel fuel decreased pour point considerably but there was no difference among the four emulsions.

Table 4: The E-Series fuel blends specifications

Fuel Specifications	E_0	E_2	E_5	E_8	E_{10}	Accuracy
Kinematic viscosity at 40 ºC (cSt)	3.1	3.2	3.7	4.0	4.1	±0.1 cSt
Density (kg/L)	0.841	0.846	0.851	0.855	0.859	±0.001 kg/L
Dynamic viscosity (cP)	25.90	26.73	31.32	33.77	35.56	±0.01 (cP)
Pour point (ºC)	-12	- 42	- 42	- 42	- 42	±1 ºC

3.2 Engine Power

Fig. 6 showed the variations of the engine power versus engine speed with different water-diesel emulsions. It can be seen that the power increased with the increase in engine speed for all the emulsions. There were more differences between engine power for the various fuel blends at higher engine speeds which verified the increase of water addition effect at higher speeds [35]. The regression analysis showed the second order polynomial relationships with very high coefficient of determination between engine power and its speed for all the fuel blends.

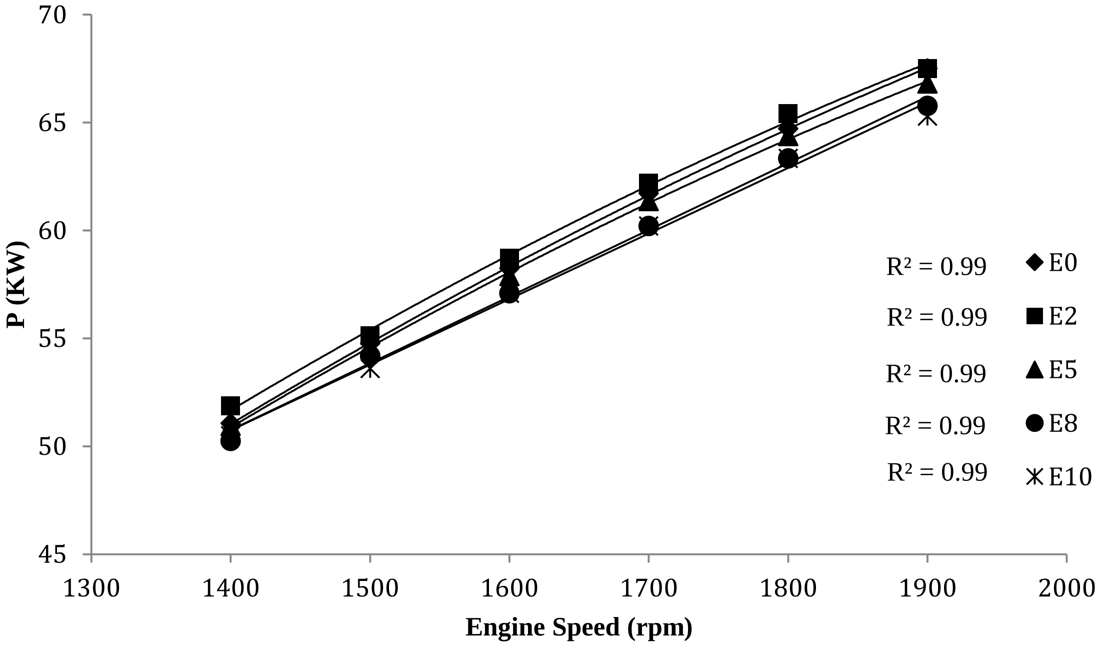


Fig. 6. Engine power output for different fuels Vs engine speed.

According to the results of ANOVA, the engine speed and fuel blend type parameters had a significant effect on the engine power. Fig. 7 revealed the results of comparing mean values of the engine power versus engine speeds and fuel blend types using Duncan's multiple range tests. The engine power increased significantly at 1% probability level when the engine speed increased. This could be due to the power stroke increment per unit time.

Adding 2% water to neat diesel fuel significantly increased the engine power output ($P < 0.01$). Qi et al. [36] attributed this increase to the effect of micro-explosions which promoted better atomization and formation of air–fuel mixture. So, a more combustible air–fuel mixture could be burned in the premixed combustion phase, which resulted in higher peak cylinder pressure and higher power output.

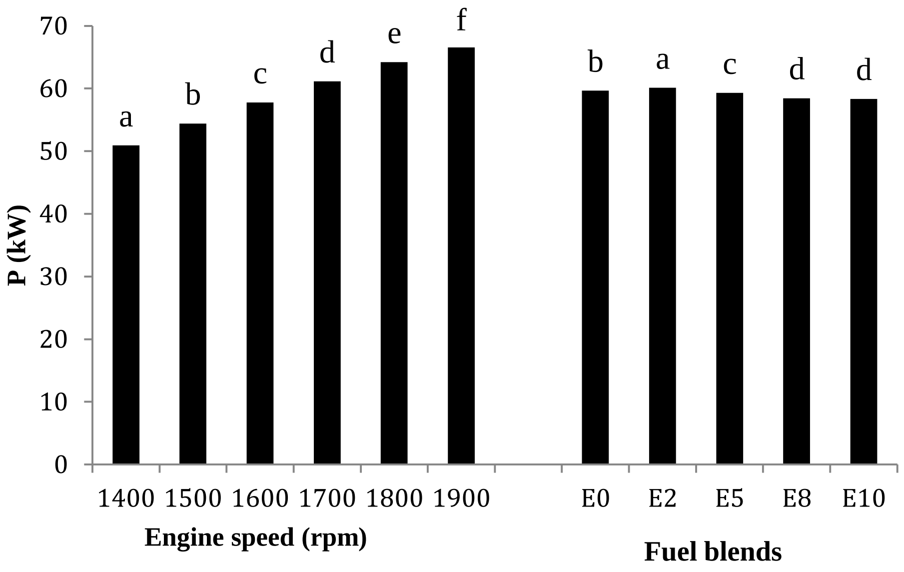


Fig. 7. The effect of engine speed and E-Series fuel blends on the engine power. Means with same letter are not significantly different.

Further increasing the water fraction in diesel fuel to 10 % vol., caused the engine power to decrease by 2%. This reduction could be attributed to a lower fuel calorific value [23] which overcomed the benefits of water-diesel emulsion. Therefore, adding a low percentage of water to fuel could yield a higher engine power. There was no significant difference ($P < 0.01$) between mean values of engine power for E_8 and E_{10}.

3.3 Engine torque

Fig. 8 shows the mean values of the engine torque versus engine speed with different water-diesel blends. The regression analysis on the experimental measurements of engine torque as a function of engine speed for each fuel blend showed a polynomial relationship with very high coefficient of correlation. The maximum engine torque was related to E_2. Like engine power, the increase in engine torque using E_2 could be due to micro explosion process which resulted in simoltaneous additional braking of the droplets, so the droplets evaporation surface increases and the mixing of the burning fuel in air improves [36]. Alahmehr [34] also reported higher torque for emulsion with low percentage of water than neat diesel.

It is noted that when the engine speed increases, mean values of engine torque decreases. This is in agreement with Alahmehr [34] who found that at higher engine speeds, due to the frictional loss and shortening the time of intake stroke, the engine cylinder cannot be fully charged, which causes a reduction of both the engine volumetric efficiency and the engine torque. So it could be concluded that depending to the engine type, the diesel quality and the type and amount of surafctant, up to certain amount of water in emulsion micro explosion phenomena can yield higher output power and torque than neat diesel.

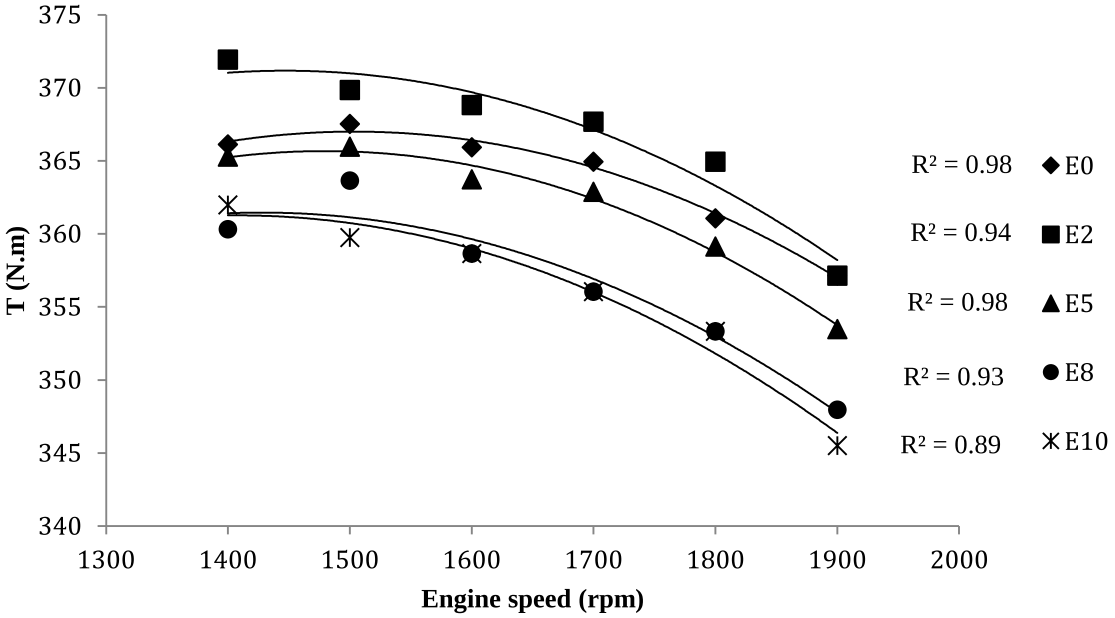


Fig. 8. Engine torque output for different fuels at varying engine speeds.

Duncan's multiple range tests to compare the mean values of the engine torque versus the engine speed (Fig. 9) showed similar results. It could be noticed that the engine torque did not change significantly ($P < 0.01$) with the increase in engine speed up to 1700 rpm. Similar trends was reported by Hassan-beygi et. al [37] which evaluated this engine fuelled by biodiesel-diesel blends.

Similarly to what was found for the engine power, ANOVA showed that engine speed and fuel blend type parameters had a significant effect at 1% probability level ($P < 0.01$) on the engine torque. From Fig. 6, it can be seen that adding water to neat diesel fuel up to 5% does not change the engine torque significantly. Although the calorific value of E_5 was definitely lower than E_0, the larger amount of oxygen content of the added water facilitated a more complete combustion process. So, mean values of the engine torque did not decrease significantly ($P < 0.01$). A further increase in the water percentage up to 8%, reduced the engine torque ($P < 0.01$) of about 1.4%, compared to the E_5 fuel blend. No significant difference was found between E_8 and E_{10}. Alahmer et. al [22] and Alahmer [34] attributed the decrease of torque with the increase in water percentage to the higher pressure on the piston caused by the steam evaporation during the compression stroke at the initial steps of the combustion process.

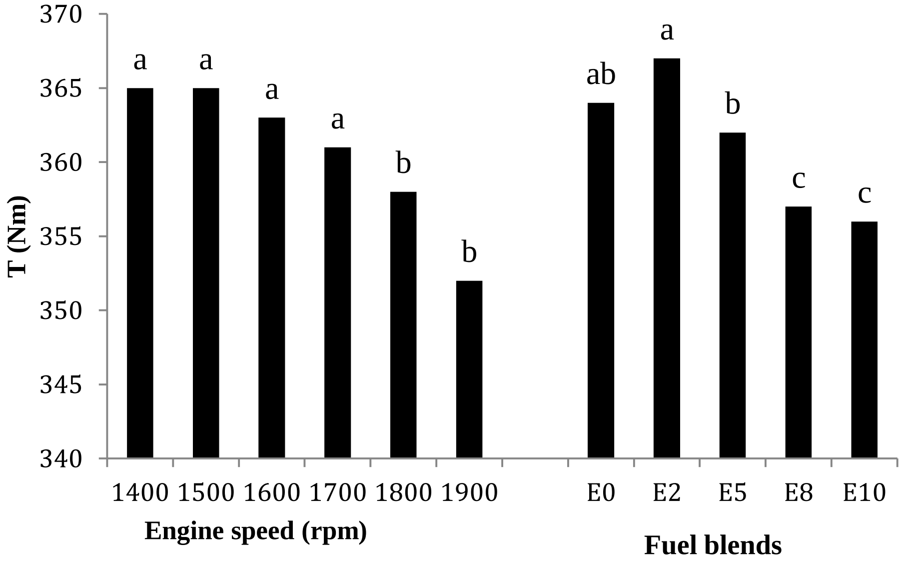


Fig. 9. The effect of engine speed and E-Series fuel blends on the engine torque. Means with same letter are not significantly different.

3.4 Engine noise emission

Good consistency was found between measured engine sound pressure level using Cool Edit Pro and sound level meter (Fig. 10) which verified the reliability of the latter.

Overall engine sound pressure level variations versus different engine speeds were shown in Fig. 11. For all fuel blends, overall sound pressure levels generally increased with the increase of engine speed from 1600 to 1900 rpm, which is normal in agricultural equipments [38, 39].

The highest and lowest noise emission was found for E_{10} at 1900 rpm and for E_2 at 1600 rpm, respectively. Combustion of diesel showed highest and lowest noise emission at 1600 rpm and 1700 rpm, respectively. In 1800 rpm there were no significant difference between all fuel blends.

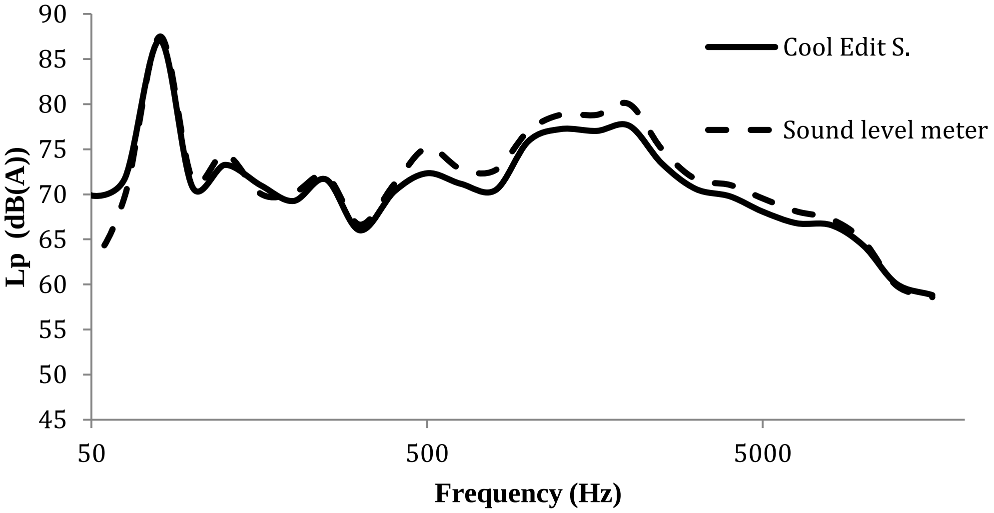


Fig. 10. 1/3rd octave band frequency domain signals of diesel engine fueled with E_{10} at full load condition.

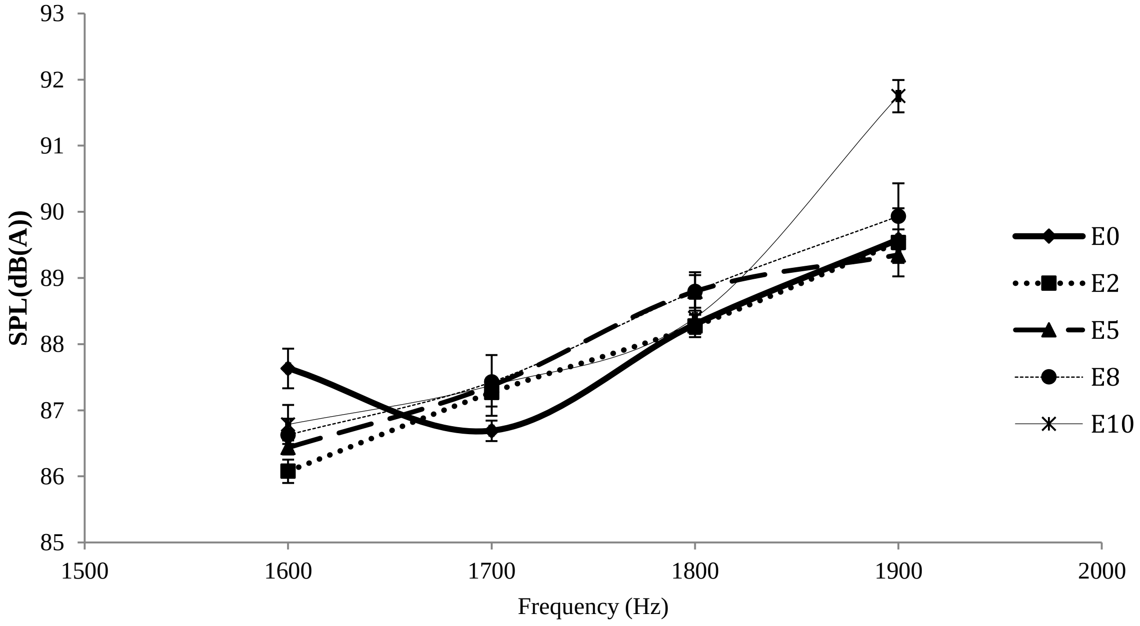


Fig. 11. Engine noise emission for different fuels at varying engine speeds

The operation of engine with neat diesel featured minimum sound pressure levels at lower engine speeds. At higher speeds, these differences did not exist and some blends showed lower noise emission than neat diesel. These could be due to lower HRR of emulsions at higher speed. At lower speed, due to having higher ignition delay, a longer time was available for emulsion to mix with air which led to higher HRR [13] and resulted in a more powerful and louder combustion. As the engine speed increased, emulsion fuel had less time to form a flammable mixture, therefore, it showed a lower peak HRR at higher engine speed [13] which countracted the effect of ignition delay increment.

Duncan's multiple range tests to compare mean values of the engine noise emission versus engine speeds, fuel blend types and engine load were shown in Fig. 12. Its Results were in agreement with Fig. 11, where noise emissions increased significantly ($P < 0.01$) with the increase in engine speed.

The presence of water in diesel increased physical and chemical ignition delay and led to higher noise emission [26] but it can be seen that except for E_2 and E_{10}, there was no significant difference between noise emissions of fuel blend types. Comparing to neat diesel, operating the diesel engine with E_2 did not increase engine noise emission. So, higher engine power and torque output by using $E_{2,}$ could introduce it as an appropriate fuel blend for using instead of neat diesel.

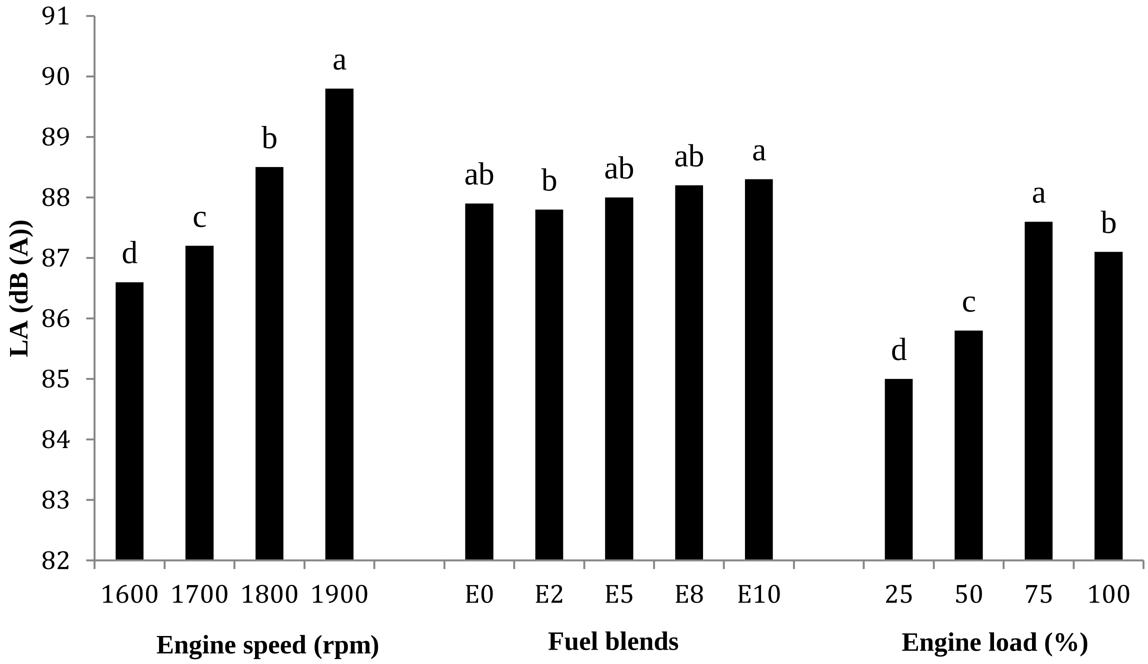


Fig. 12. The effect of engine speed, E-Series fuel blends and engine load on the engine noise emission. Means with same letter are not significantly different.

Significant increases in sound pressure level ($P < 0.01$) were found as engine loading was raised from 25 % to 75%, but at full load condition noise emission decreased significantly ($P < 0.01$). The significant increase in sound pressure level from 25 % to 75 % load may be due to higher thermal efficiency which helps to have more powerful and louder combustion.

It was reported that thermal efficiency increases when increasing engine load until 75% but with further increase in engine load there is no such increase in thermal efficiency [40]. On the other hand with increase in engine load, ignition delay showed constant decrease until full load [41]. Since thermal efficiency impact for engine loading condition higher than 75 % was negligible, the decrease in sound pressure level with the increase in engine load may be due to the ignition delay decrement.

Conclusions

The conclusions drawn from this research work are as follows:

1. The effects of fuel blend type and engine speed parameters were significant on the engine power and but no such effects were found for engine torque.

2. A larger amount of oxygen from added water facilitates a more complete combustion process. So, adding water to neat diesel fuel up to 5% does not change the engine torque significantly.

3. Generally, the presence of water increased ignition delay and engine noise emission.

4. For the E_2 fuel blend, with the highest engine power and torque, noise emission did not have significant difference with neat diesel. So, it could be suggested as an appropriate alternative for neat diesel fuel.

5. Lower peak HRR at higher engine speed led to weaker and more silent combustion for emulsions than neat diesel which counteracted the effect of ignition delay increment.

6. Thermal efficiency increase from 25 % to 75 % engine load may lead to more powerful and louder combustion.

7. Sound pressure level reduction from 75 % to 100 % engine load may be due to the effect of ignition delay decrement.

Acknowledgment

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