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Combustion Characteristics, Performance and Emissions of a Diesel Engine Fuelled with Water/Diesel Emulsions

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The impact of two different formulations of water-in-diesel emulsions (WDE1 and WDE2) and diesel fuel containing 10 % of palm oil biodiesel (B10) on the combustion characteristics, performance and pollutant emissions of an automotive diesel engine was evaluated at 1,800 rpm and two different torque levels (66 Nm and 99 Nm). Both emulsions exhibited longer ignition delays, in comparison with B10. The premixed combustion phase was drastically increased while the diffusive combustion phase was reduced, and the combustion duration remained almost invariable respect to B10 fuel. Combustion efficiency, determined through the ratio between cumulative heat release rate and lower heating value was slightly deteriorated at low torque however an improvement was observed at 99 Nm. On the other hand, bulk in-cylinder temperature showed a strong dependence on emulsion formulation and operating conditions, exhibiting a decrease at low load due to the heat of vaporization of water contained in the emulsions.
Higher brake specific fuel consumptions (BSFC) and equivalence ratios were obtained with both emulsions due to their lower heating value compared to B10. CO and THC emissions increased in comparison to B10. On the other hand, NO_x emissions were decreased at both engine-operating modes reaching a reduction up to 40 % with the WDE1 emulsion while particulate matter emissions were highly water content dependent WDE1 and reached reductions up to 11 % respect to B10 for WDE1.
From this experimental work, it was concluded that depending on engine operating mode and water content, the water in diesel emulsions are efficient fuels, which can be directly used in conventional diesel engines showing a potential to reduce simultaneously NO_x emissions and particulate matter. More research work is being carried out at this extent in order to assess the impact of the optimum water-in-diesel emulsion on engine durability, non-regulated emissions and particle matter biologic activity.

1. Introduction

Diesel engines play an important role in numerous civilian and industrial applications. Among their advantages are fuel economy, high thermal efficiency, durability and heavy-duty applications (Pischinger, 1998). However, pollution caused by these engines has been considered a serious problem for air quality and efforts are underway to minimize exhaust emissions from diesel engines (Tasić, 2014).
Strategies for reducing diesel engine emissions are diverse and range from fuel reformulations to engine retrofits.
Nevertheless, most of the techniques that are used to reduce NO_x, lead to an increase in smoke and PM and viceversa (Eckert, 2008). An alternative for reducing simultaneously levels of NO_x and PM (Ithin and Ahmand, 2015) is reformulation the fuel adding water or a lower volatility compound like a short chain alcohol.
Several researchers have shown that water introduction into diesel fuel by emulsification may help to improve atomization and mixing, which can be attributed to droplet micro-explosions (Yang et al., 2013) and an increased fuel jet momentum (Armas et al., 2005). Micro-explosion is a term used to define the explosive boiling of the water inside the emulsion which produces the disruption of the primary drops and the violent ejection of smaller drops into the combustion volume (Fu, 2006). Such secondary drops

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evaporate very quickly and are dispersed in a big volume, improving fuel/air mixing and the overall combustion efficiency (Califano, 2014). The improvement in homogenization and the presence OH radicals formed from water improve PM and unconverted hydrocarbon oxidation (Lif and Holmeberg, 2006). On the other hand, NO_x are diminished by the peak flame temperature reduction derived from water introduction and the dilution of air/fuel mixture provided by greater air entrance into the fuel jet (Greeves et al., 1976).
Regarding combustion and performance parameters, most authors report an increased ignition delay (Alahmer, 2013), and reduction in NO_x and PM emissions, but results about thermal efficiency and brake specific fuel consumption are diverse and highly dependent on the engine and load conditions, furthermore most papers do not show results about combustion characteristics analysis.
The purpose of this work is to evaluate the effect of water content and load on the the mechanical performance and emissions of an automotive diesel engine, but analysing these results in the light of combustion characteristics.

2. Experimental

2.1 Emulsions preparation and characterization

Water in diesel emulsions were prepared using a hydrodynamic cavitation device (EMULSOR 2000, CT Systems). The structure of the dispersions of diesel fuel containing 10 % of palm oil biodiesel (B10), 10 % (WDE1) and 16.67 % (WDE2) of potable water and a mixture of non-ionic surfactants Span80-Tween80, were characterized using a dynamic light scattering instrument (Zetasizer Nano ZS90). The stability of emulsions was estimated monitoring the droplets size distribution as function of storage time. It was also measured for all the tested fuels, API gravity (ASTM D287), heating value (ASTM D240), viscosity (ASTM D445), pour point (ASTM D97), copper strip corrosion (ASTM D130), cetane index (ASTM D976), flash point (ASTM D93) and simulated distillation (ASTM D86).

2.2 Experimental setup

A diesel engine test bed including a 2.5 L, turbocharged, direct injection, four cylinders Isuzu 4JA1 pre-Euro automotive diesel engine, was used to study the performance (torque, power, efficiency, specific fuel consumption) and emissions (nitrogen oxides, particulate matter and carbon monoxide) generated from combustion of B10, and emulsified fuels. Other specifications of the engine are showed in Table 1.

Table 1: Engine characteristics

Diameter/stroke (mm/mm)	93 / 92
Compression ratio	18.4:1
Injector pump	Mechanical rotary
Injection pressure (bar)	200
Maximum power	59 kW at 4,100 rpm
Maximum torque	170 Nm at 2,300 rpm

Table 2: Physicochemical properties of emulsions

Properties	B10	WDE1	WDE2
°API at 288 K	33.7	31.1	29.6
Simulated distillation (K) IBP-FBP	453-643	373-641	373-640
Heating value (MJ/kg)	45.9	37.5	38.6
Viscosity (m^2/s) at 313 K	$4.02 \cdot 10^{-6}$	$6.05 \cdot 10^{-6}$	$6.15 \cdot 10^{-6}$
Cetane Index	52.13	45.57	43.02
Surface tension (N/m) (298 K)	$26.8 \cdot 10^{-3}$	$28.58 \cdot 10^{-3}$	$28.58 \cdot 10^{-3}$
Flash point (K)	345	378	377
Cooper corrosion	1.A	1.A	1.A
Pour point (K)	-261	-261	-261

The engine is coupled to an electromagnetic dynamometer and engine loads are controlled manually by an electronic control system. Exhaust gases are analysed by gas analyser equipment (AVL Dicom 4000), air volumetric flow is measured by Magnetrol TA2 hot wire device and measurement of fuel mass by a flow through a precision balance system. For particulate matter collection was utilized a mini-dilution tunnel, used to determine the mass of particles in the diluted exhaust gas.
Operating conditions used for the test were selected considering that these fuels may be used for power generation, speed was fixed at 1,800 rpm and two torque values were tested 66 Nm (3.32 bar bmep) and

99 Nm (4.98 bar) for each fuel. These values varied in a range of ± 10 rpm and ± 3 Nm, according to the equipment precision and electronic control system available.

3. Results and discussion

3.1 Emulsions characterization

Particle size distribution showed both emulsions had particles between 0.5 – 5 μm and these structures were kept during 9 days, meaning emulsions were completely stable during this period. Other properties measured for the fuels are presented in Table 2.

3.2 Emulsions impact on combustion process

Figure 1 shows the results of the combustion thermodynamic diagnostic for the tested fuels a two load conditions. Instantaneous in-cylinder pressure increased with the load degree due to the increased amount of fuel injected and both emulsions exhibited a slight increase in maximum combustion pressures compared to B10, especially at medium load. It was expected that the in-cylinder pressure curves were the same for all the fuels, since the power on the engine shaft was fixed, these differences may be due to inaccuracies of the electronic control system on the torque (± 1 Nm) and the engine speed (± 10 rpm) shown in Table 3, or to the effect that emulsions might have on the starting angle injection because of the engine's pump is completely mechanical and depends entirely on fuel properties (density, viscosity and bulk modulus). Unfortunately injection angle was not registered.

Table 3: Torque and rpm (desired value vs. real value measured)

	Rpm	Torque	Rpm	Torque
Desired value	1,800	66	1,800	99
WDE1	1,800	65	1,800	96.76
WDE2	1,800	64.86	1,800	96.99
B10	1,791	64.92	1,794	96.51

A higher bulk modulus may have caused an advancement in the start of injection angle, causing the greater maximum combustion in-cylinder pressure. At 200 bar, the bulk modulus for water is between 2,350 and 2,375 MPa compared to diesel value, which is about 1,300 MPa at the same pressure (Lapuerta et al., 2012).

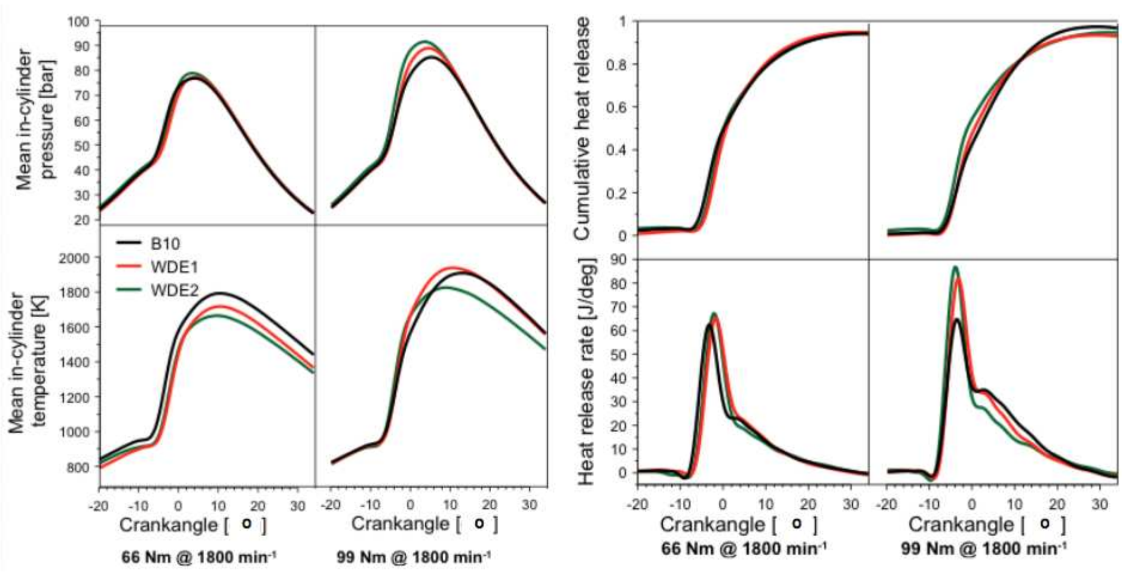

Figure 1. Combustion diagnostic

On his behalf, the average temperature in the chamber was increased with the load as expected, due to the increase in the relative equivalence ratio. Regarding the fuel effect on temperature, it was noticed a drop in the average temperature, using the emulsions, being greater for WDE2 than for WDE1; this may be due to a combination of both the enthalpy of vaporization of water and the uncertainties associated with the measurement of the trapped mass at the closing of the intake valve as the temperature is calculated from the state equation of an ideal gas (Benjumea et al., 2009). At lower bmep (3.32 bar), where the injected mass was lower, vaporization enthalpy of water had a greatest impact on cylinder temperature than the bulk modulus and at 4.98 bar was observed that WDE2 showed greater cylinder pressure due to their higher bulk modulus, and yet their temperature profile was the lowest among the three fuels, due to its water content. One would expect that the temperature profile of WDE1 was in between and B10, but it was not, perhaps due to the uncertainty in the trapped mass of which mention was made up.

The cumulative rate of heat release, conventionally used to determine the duration of combustion, and the rate or speed at which fuel is burned (Heywood, 1988), showed that both emulsions at low load induced a delayed on the beginning of combustion, and a slight decrease in the duration of combustion, caused by the major portion of premixed combustion than B10 and this effect was more pronounced with the emulsion with higher water content.

Table 4, summarizes the key parameters of thermodynamic diagnostic, including the combustion noise or coefficient of variation of the indicated mean pressure (COV), defined as ratio of the standard deviation of the mean pressure indicated on medium pressure average value indicated for a total of 100 recorded curves. At lower bmep COV was greater for both emulsions compared to diesel. However at medium load both emulsions improved and even exceeded COV value for B10, being WDE1 the one with cyclic variability (COV = 0.856).

We conclude that emulsions followed the same combustion pattern than B10, defined as ignition delay plus premixed combustion plus diffusive combustion with better combustion than B10 at medium load and noisier at low loads.

Table 4: Combustion parameters

	66 Nm			99 Nm		
	WED1	WDE2	B10	WED1	WDE2	B10
COV (%)	2.121	1.205	0.896	1.053	1.49	1.978
T_{MAX} (K)	1,717	1,664	1,792	1,938	1,825	1,908
P_{MAX} (bar)	77.22	78.81	76.82	88.89	91.48	85.24

3.3 Emulsions impact on mechanical performance

In Figure 2a, it is shown the comparison of engine mechanical performance for all the fuels. The relative equivalence ratio (ϕ), increased with load due to the greater mass of injected fuel. The two emulsions required greater values of ϕ to achieve the same bmep than B10, due to its lower energy content. In this case calculation was based on diesel stoichiometric equivalence ratio for all fuels, since was assumed that water was not involved in combustion. On the other hand, brake specific fuel consumption (BSFC) increased with both emulsions compared to B10, being greater for WDE2, which contains more water. This result is due to the emulsions lower calorific value compared to B10, since the experiment was performed at equal shaft power. At low and medium load it was observed a significant decrease in efficiency compared B10 according to the water content of the emulsion was observed.

In summary, both emulsions showed an increased relative equivalence ratio and specific fuel consumption because of their lower energy content. Thermal efficiency tended to decrease at tested conditions compared to B10, probably due to the effect on emulsions combustion pattern discussed in the previous section.

3.4 Emulsions impact pollutant emissions

In Figure 2b gaseous emissions as well as particulate matter (PM) are presented. CO was increased when using WDE1 and WDE2 at both load conditions tested and it can be attributed to the low temperature in the combustion chamber. On his behalf, total hydrocarbon emissions (THC), which are mainly due to incomplete fuel combustion, were not affected by the use of emulsified fuels (see Figure 3).

NO_x emissions decreased with both emulsions compared to B10, regardless of the engine load and there was not significant variation between the WDE1 and WDE2. This reduction is usually related to the cooling effect provided by the water evaporation because an important part of NO_x emissions in a diesel follows Zeldovich mechanism, according to which, more NO_x are produced at higher temperatures (Eckert, 2008).

Finally, our results showed that PM highly depends on water content, for WDE1 it a reduction around 10 % and for WDE is was a increasing in PM, is attributable to the fact that the negative effect of temperature reduction for PM oxidation is higher than the effect of the improved homogenization or OH radicals presence.

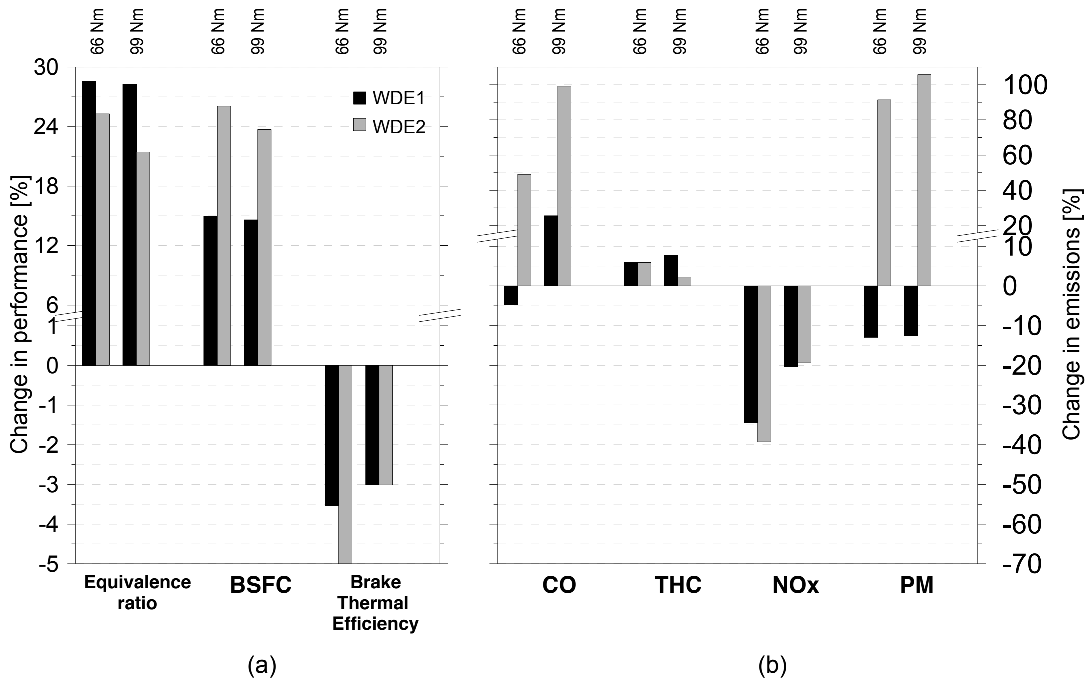

Figure 2.Relative changes in performance (a) and emissions (b) of the emulsified fuel containing 10 % and 16.67 %w/w water compared to B10

4. Conclusions

Emulsified fuels tested functioned properly in terms cyclic variability. Maximum coefficient of variation at the tested condition was 2.1 % and driveability problems usually occurs when COV exceed about 10 %.
Both emulsified fuels showed higher ignition delays and higher proportion of premixed combustion phase compared to the commercial diesel B10 tested, despite it could affect NOx emissions and performance, there was a reduction in NO_x up to 40 % for both emulsions at the tested conditions.
As particulate emissions are highly dependent on temperature, reducing water content could mitigate the temperature reduction caused by water vaporisation in emulsions and conduce reductions around 10 % in particulate matter as has been reported by other authors.
It is necessary evaluate the impact of emulsified fuels on engine durability, non-regulated emissions and particulate matter biologic activity.

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