Characterization of light duty Diesel engine pollutant emissions using water-emulsified fuel

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Abstract

In this work, the effect of water–oil emulsions on the engine performance and on the main pollutant emissions, NOx, total hydrocarbons (THC), soot, particulate matter (PM) and its composition, was studied. A turbocharger intercooler indirect injection (IDI) Diesel engine was tested under five different steady state operating conditions, selected from the transient cycle for light duty vehicles established in the European Emission Directive 70/220. Tests were performed using a commercial fuel as a reference and an emulsified fuel for each operating condition. Results reported here suggest that the water emulsification has a potential to slightly improve the brake efficiency and to significantly reduce the formation of thermal NO, soot, hydrocarbons and PM in the Diesel engine.

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1. Introduction

The trend towards more stringent regulations on emissions has been an important driving force in the search for internal combustion (IC) engines more environmentally friendly. The literature on this topic can be classified into three groups. The first group contains works dealing with the development of systems to improve fuel mixture and combustion [1]. The second group of works addresses the study of alternative fuels and additives for conventional ones [2]. The third group of recently published papers report on new post-treatment devices [3].

The present work belongs to the second group of studies reporting an experimental investigation about the influence of water–oil emulsifying on the main pollutant emissions, namely particulate matter (PM), total gaseous hydrocarbons (THC) and NOx, in an IDI Diesel vehicle engine tested under different operating modes, selected as characteristic conditions of the European cycle for the certification of light duty engines. The PM emissions have been studied in more detail, analysing the emulsification-induced changes in the amount, morphology and composition of these particularly toxic emissions.

All the reviewed works about preparation and use of water–Diesel emulsions have been focused on different aspects of the effects of this fuel on the engine performance and emissions. In general, the main conclusions of these works can be summarized as follows:

1.1. Physical properties and their effects on injection and mixing processes

The main affecting properties are density, viscosity and bulk modulus of elasticity. In all cases, an increase of the value of these properties with water concentration was observed. In case of viscosity, Sawa et al. [4] observed an increase proportional to the ratio between surface area Sp/Se. Se is the surface area of emulsified fuel and Sp is the sum of surface area of distributed water droplets, both areas being assumed spherical. In case of density, the authors concluded that emulsion density is a little smaller than that

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obtained from averaging the fuel and water densities. The emulsion density value depends on the amount air bubbles in the emulsion as a result of the preparation process. Likewise, the authors concluded that an increase of air bubbles carries a decrease of bulk modulus.

The increased viscosity of emulsified fuel tends to advance injection timing in some injection systems due to the modification of the dynamics of the command hydraulic system. This effect is mainly due to the flow variations through the control circuit [4–6].

With the use of emulsions an improvement in mixing process was observed. This improvement is caused by two confirmed phenomena. The first, consists of an additional momentum in jet behaviour [6,7]. The second and more important, is based on the internal droplet micro-explosions of water, which produce a secondary atomisation, thus improving the mixing process. [8–13]. The mentioned micro-explosion phenomenon is induced by the volatility difference between the water and the fuel [14,15].

1.2. Effect on combustion process and emissions

In an important number of reviewed studies, the authors have observed that an increase of water concentration in the emulsion produce a significant increase in the ignition delay, due to the heat absorption by water vaporisation in the fuel jet [5,7,8,10,13,16–20].

Another proven benefit of the emulsion as Diesel fuel is that the heat absorption by water vaporization causes a decrease of local adiabatic flame temperature and therefore reduces the chemical reaction in gas phase to produce thermal NO, depending, in some cases, of engine operation mode [6,7,10,12,18,21–23].

The improvement on vaporization and mixing processes leads to a shorter combustion reaction. This effect can help to reduce soot, PM, CO and HC formation [4–10,12,13,16–21,23,24].

1.3. Effect on engine performance

The effects of the emulsified fuel on the engine performance are different from one study to another. The obtained results depend, mainly, on the engine operation mode [5,6,10,12,16,19,25–28], type and tuning of the injection system [17,18,22], and finally, on the optimised combustion chamber configuration [29]. When the emulsified fuel is used, the most probable reason to obtain improvement in specific fuel consumption or thermal efficiency is the reduction of heat losses [30,31].

2. Fuel properties

Two fuels were tested: a commercial fuel and the same fuel after emulsification with a 10% w/w of water. Their main characteristics are summarized in Table 1 [32].

In particular, the changes in density, viscosity and heating value respect to the commercial fuel must be noticed. The density is a measure of the mixture efficiency. The viscosity must be close to that of the reference fuel in order to avoid problems with the injectors. The heating value affects the effective power.

The summarized formula of both fuels is calculated from the elemental analysis and the molecular weight.

2.1. Production of emulsified fuel

Fig. 1 shows a scheme of the device used for the preparation of the emulsified fuel. This fuel was produced using a Hartmann whistle [33] coupled to a gear pump and two tanks, one for water and the other for the Diesel fuel with the surfactants recommended by Repsol-YPF company (polyethylenglycole monoleate and sorbitole sesquioleate).
2.2. Thermo-chemical properties

The Joback group contribution method [34] was used to estimate the specific heat at constant pressure and the standard enthalpy of formation in the reference Diesel fuel:

\[
\frac{C_p}{R} = -1.88239 + 0.13899T - 8.2679 \times 10^{-5}T^2 \\
+ 1.8934 \times 10^{-8}T^3 + 6.8157 \times 10^{-15}T^4
\]

\[
\frac{h_f^0}{R} = -50250.69 \text{ K}
\]

For water, the thermo-chemical properties were calculated using the thermo-dynamical data base included in the CHEMKIN III [35]. The fits are obtained using the following correlations until 1000 K:

\[
\frac{C_p}{R} = 3.38684 + 0.003475T - 6.355 \times 10^{-6}T^2 \\
+ 6.969 \times 10^{-9}T^3 - 2.507 \times 10^{-12}T^4
\]

\[
\frac{h_f^0}{R} = 29899.21 \text{ K}
\]

The vaporization enthalpy of the water at standard conditions is 2440 kJ/kg.

This data was introduced in a chemical equilibrium model [36] which considers 29 chemical species (\(N_2, O_2, CO_2, H_2O, CO, H_2, NO, OH, N, H, O, Ar, N_2O, NO_2, HO_2, NH_3, NH_2, NH, CN, HCN, NCO, S, S_2, SO, SO_2, SO_3, HS, H_2S, COS\)) to calculate the adiabatic flame temperature at constant pressure. A pressure of 80 bar, temperature of 900 K and stoichiometric A/F ratio were taken as typical Diesel in-cylinder conditions at the start of combustion (see Table 1).

3. Experimental set-up for testing and analysis

3.1. Engine test bed and instrumentation

The tested engine was a Renault F8Q turbocharged intercooler IDI Diesel, similar to those commonly used in European passenger car. The engine was coupled to a Schenck hydraulic brake and equipped with the instrumentation for its control and for the measurement of all the parameters affecting emissions as shown in Fig. 2.

This engine was tested in five different operating conditions (Table 2), selected among the collection of steady stages [37] which reproduce the sequence of operating conditions that the vehicles equipped with this type of engines must follow during the transient cycle established in the European Emission Directive 70/220, amendment 2001/C 240 E/01 [38]. In all tests the lubricant oil was a SAE 15W40 supplied by Repsol-YPF.

Particulate matter was collected in a partial dilution mini-tunnel (Nova Microtroll) on glass fibre filters covered by Teflon, as stated by regulations. The filters were conditioned in a climatic chamber (Minitest CCM-0/81), before and after the collection, in order to maintain constant temperature and humidity. An analytical balance was placed inside the chamber to perform the weightings under these conditions. The collection and conditioning procedure was optimised as described by Lapuerta et al. [39].

Fig. 2. Engine test bed.
Further insight into the exhaust composition was gained with the measurement of hydrocarbon and nitrogen oxides, detected by flame ionisation (Amluk 2010uP) and gas-phase chemiluminescence (Beckman 951A), respectively. The smoke opacity of the exhaust gas was measured by a smokemeter (AVL 415).

### 3.2. Instrumentation and software for chemical and morphological analysis

After weighing, the filters with particles were subjected to an optimised Soxhlet extraction method [40]. In this process, the soluble organic fraction (SOF) of the particulate matter was analysed by gas chromatography (Hewlett Packard 6890), and the insoluble fraction (ISF) was measured by high performance liquid chromatography (Gibson 802C with an ionic conductivity detector 732 U Methrom). The SOF chromatograms allowed distinguishing the origin of soluble organic hydrocarbons by comparison with those from lubricant oil and fuel [41].

Similar filter-deposited samples to those used in the chemical analysis were studied by Scanning Electronic Microscopy (SEM). In spite of the advantages of on-line methods (SMPS, ELPI, etc.), the procedure used here can be easily integrated in the certification methodology for Diesel vehicles, and has proved to correlate well with tendencies obtained from on-line methods.

Eight SEM images for each filter paper (four at 500 × and four at 8000 ×) were obtained and subjected to a digital analysis developed in Matlab. The particulate matter morphology was quantified through the number of particles per filter surface unit, the arithmetical mean diameter and Sauter mean diameter. This program modifies the contrast in the 500 magnification images in order to make the texture more uniform [42], subtracts the fibbers, and finally, binarizes into black/white images. The nanoparticles, smaller than the pixel size, were subjected to another procedure from SEM images with 8000 magnification, where fibbers filter do not appear. The final outputs are the particle size distribution, the standard deviation and several characteristic average diameters, such as the arithmetic or Sauter mean ones. The good qualitative agreement between these particle size distributions and those obtained with on-line equipment validated this analytical procedure [43].

### 4. Effect of emulsified fuel on engine performance

All the results shown here have been obtained as the main value of four measurements for every parameter in each operating mode, neglecting values with discrepancies above 2%.

All the results from the emulsified fuel study have been referred to the Diesel fuel mass consumption. The Figs. 3–5 show the results obtained in terms of engine performance, thermo-dynamical diagnostic (rate of heat release and heat release law) and pollutant emissions, respectively.

The improvement in the brake efficiency at mode E (Fig. 3) can be understood from the evolution of the needle lift and the cylinder pressure signals, both represented in Fig. 4. The higher viscosity of the emulsified fuel yields earlier injection (always compared with commercial fuel). However, this is compensated by the increase in the delay time induced by the water content in the emulsion and therefore the beginning of the heat release in the main chamber is detected approximately at the same time as with the reference fuel. From this point on, the combustion itself is faster for the emulsion, which explains the increased brake efficiency [44].

In mode H, a similar injection advance was also observed. In fact, for this mode, the heat release in the main chamber should begin earlier for the emulsion than for

![Fig. 3. Engine performances for both tested fuels.](image-url)
the reference Diesel fuel, because the delay time under these conditions is much shorter. However, this effect is not noticed because the beginning of the combustion is hidden in the pre-chamber, where no pressure transducer is located.

The faster combustion of the emulsion, a prerequisite to explain the previous observations, can be explained by the improvement in the spray atomisation due to the water drops micro-explosions [13,44].

5. Effect of emulsified fuel on engine emissions

Fig. 5(a) shows the expected improvements in the NO\textsubscript{x} specific emissions, explained by the introduction of liquid water in the combustion process. The vaporization and sensible water heats reduce the local adiabatic flame temperature and thus NO\textsubscript{x} formation [18].

Fig. 5(b) and (c) show the measured reduction in soot and unburned hydrocarbons emissions, respectively. The observed reduction in soot emissions agrees with the results reported in previous works [9,13,18,44]. As mentioned in the introduction, the micro-explosion phenomenon in the emulsified fuel is caused by the volatility differences between water and Diesel fuel. This violent disintegration disperses the fine droplets and consequently enhances the fuel–air mixing in the combustion chamber [12,44], which helps reducing the formation of soot and THC. Additionally, the increased amount of OH radicals from water dissociation also reduces the formation of soot because high radical concentrations promote carbon oxidation to CO and CO\textsubscript{2}, thereby limiting carbon availability for the formation of soot precursors [45].

6. Effect of emulsified fuel on particulate composition, origin and morphology

The SOF/ISF ratio indicates the amount of organic compounds adsorbed on the surface of the soot nuclei (per unit mass). The interest of this coefficient lies on that it gives the degree of saturation of the porous and solid substrate of the particles, regardless their surface and size.

Fig. 5. Specific emissions in all operating modes.
A decrease in the relative adsorption with increasing load can be observed in Fig. 6(a). Two factors contribute to this trend: First, the highest rate of soot formation produces a higher probability of agglomeration, with the subsequent reduction of the surface/volume ratio of the particles, and therefore of its adsorption capacity. Second, the higher exhaust temperature favours the adsorption of gas hydrocarbons rather than liquid hydrocarbons. The larger specific volume of the gas hydrocarbons yields a smaller soluble mass adsorbed than in the case of condensed hydrocarbons.

The decrease of the SOF/ISF ratio when using the emulsified fuel with respect to the Diesel fuel (Fig. 6(a)), is mainly explained by the reduction in THC emissions. The higher porosity of the emitted particulate matter using emulsion, as referenced by different authors[9,44], does not compensate the mentioned decrease.

In any case, it is interesting to note the consistency between the insoluble fraction of PM and soot emissions (Fig. 5(b)), on one side, and between the extracted SOF from PM and the resulting emissions of THC (Fig. 5(c)), on the other side. Both results have the same trends with varying load for both fuels.

The origin of the hydrocarbons in the SOF of the emitted PM when using the emulsified fuel is very similar to that in the case of the reference fuel (Fig. 6(b)).

As can be seen in Table 1, the sulphur content is very similar in both fuels. In fact, the measured sulphates specific emissions were nearly the same [42]. The same happens with the specific emissions of nitrogen salts (Fig. 6(b)).

After the image processing routine described above, no significant differences were obtained for the arithmetic and Sauter mean diameters. The same is applicable to the particle number per filter surface unit (see Fig. 7).

7. Conclusions

A water–Diesel emulsion was studied in an IDI Diesel engine to clarify the changes in the main pollutant emissions, especially in the composition and morphology of particulate matter.

The study of the emulsified fuel showed that the fuel viscosity affects the hydraulic injection control system,
causing an advanced injection and in consequence, advanced combustion process.

The use of the emulsified fuel improves the engine efficiency in certain operating modes. This result confirms the necessity of a more exhaustive study combining emulsion characteristics with tuning of engine parameters.

For the operating modes studied here, a reduction of the measured pollutant emissions (NO<sub>x</sub>, HC, soot and particulate matter) was observed when the emulsion was used. Moreover, similar trends were observed between the hydrocarbons emissions and those of soluble organic compounds, on one hand, and between the soot emissions and the insoluble fraction obtained from the chemical characterization of the particles, on the other hand.

The use of the emulsified fuel reduces the adsorption of the hydrocarbons and, therefore, the SOF/ISF ratio remains below that obtained with the reference fuel. This is probably caused by the reduction on emitted hydrocarbons which is consequence of the enhanced fuel/air mixing.

There are no significant differences in the arithmetic and Sauter mean particle diameters neither from different loads nor between the emulsion and the commercial fuel.

In general, the results reported here suggest that the water emulsification has a potential to slightly improve the brake efficiency and to significantly reduce the formation of thermal NO, soot, hydrocarbons and PM in the Diesel engine. Further, experimental work for optimising the emulsion formulation in terms of water content and internal structure is recommended.

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