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# Performance, combustion, and emissions in a diesel engine operated with fuel-in-water emulsions based on lignin

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## HIGHLIGHTS

- Fuel-in-water emulsion was tested in a direct injection diesel engine.
- Emulsion was stabilized by an industrial wood lignin with water as continuous phase.
- Using effective fuel content, emulsion produces lower fuel consumption.
- Pollutant emissions for emulsions are lower for most conditions than the base fuels.

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## ABSTRACT

We report for the first time on the use of water-continuous emulsions stabilized by a bio-based macromolecule in a compression-ignition diesel engine and compare their performance, combustion and emissions against the base fuels (diesel, biodiesel, and jet fuel). For this purpose, high internal phase ratio emulsions (70:30 fuel-to-water) were produced by mechanical emulsification using carboxymethylated wood lignin as stabilizer. Combusting experiments were performed with the engine operating at 2000 rpm under three loads (0, 1.26 and 3.26 bar brake mean effective pressure, BMEP). Engine performance, in-cylinder combustion, and exhaust emissions were monitored and compared for the fuels tested. At no load condition and when compared to the respective base (single phase) fuels, an increase in the indicated work was observed for diesel and biodiesel emulsions. Compared to the base fuels, the emulsions resulted in higher engine mechanical efficiency at 1.26 and 3.26 bar BMEP except for jet fuel emulsion at 1.26 bar. Additionally, they displayed a lower brake specific fuel consumption (BSFC), if calculated on the basis of effective fuel content discounting emulsion water, and higher brake thermal efficiency. Compared to the base fuel, the respective emulsions generally presented lower peak in-cylinder pressure, lower heat release rates, and longer ignition delays at 1.26 bar and 3.26 bar BMEP; the opposite effect was observed at no-load conditions. Remarkably, a large reduction of nitrogen oxides ($NO_x$) emissions was noted in the combustion of the fuel emulsions, which was accompanied with a relatively higher carbon monoxide (CO) release at 1.26 and 3.26 bar (at 0 bar BMEP, the emulsions produced less CO emissions). The effect of emulsions on hydrocarbon emissions and smoke opacity depended on the fuel type and the engine load. Overall, it is concluded that while reports on fuel emulsions involve oil-continuous systems, the proposed water-continuous alternative represents an opportunity for diesel engines, whereby the fuel is dispersed as micrometric droplets for improved combustion and reduced emissions. At the same time, the fuel emulsion formulation takes advantage of the surface activity and high calorific value of widely available, inexpensive lignin stabilizers, making the proposed system a viable option towards cleaner or fully bio-based fuels.



## 1. Introduction

The US Environmental Protection Agency (EPA) is set to introduce new motor vehicle emission standards starting in 2017. The program will seek to lower vehicle emissions and reduce the sulfur

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content of gasoline. Moreover, it is estimated that by 2030 it will reduce vehicle nitrogen oxides ($NO_x$) emissions by 25%, carbon monoxide (CO) emissions by 24% and direct particulate matter (PM) by 10% [1]. Engine manufactures will need to adopt methodologies to meet the requirements of the new standard. Methods typically used to reduce emissions for diesel engines consider use of alternative fuels, introduction of water into the combustion chamber and application of measures to tackle individual controlled emissions such as particulate filters and oxidation catalysts. Although effective in reducing engine emissions, some of these systems are not cost effective, may require extensive modifications to the vehicle, and, in some cases, emissions are reduced at the cost of engine performance. After treatment systems in use particularly for diesel engines need to be well maintained for the engines to continue to meet emissions requirements. Biofuels as alternative fuels, on the other hand, can be very effective in reducing engine emissions, coupled with other benefits including energy security, lower toxicity, higher lubrication, local availability, and sustainability [2].

The use of emulsions of water and fuel can be an effective means by which regulated pollutant emissions can be reduced. The addition of water to fuel has the additional benefit of reducing the fuel consumption. An emulsion is a mixture of two or more liquids in which one (the dispersed phase) is present as droplets, of microscopic or ultramicroscopic size, stabilized and distributed throughout the other, continuous phase [3]. It is created by the agitation of two fluids in the presence of amphiphile molecules (surfactants, for example) that typically contain both polar and non-polar moieties so that they adsorb and stabilize the interface and reduce the interfacial tension, leading to kinetically-stable multi-phase systems [4]. Fuel emulsions are produced when fuel and water are mixed together in the presence of a surfactant with either water as the continuous phase and the fuel as the dispersed phase or vice versa. A number of reports exists on the use of emulsions containing waste cooking oil [5], animal fat [6], biofuel [7] and diesels [8–13]. Three – phase emulsions [14–16] and diesel-ethanol emulsions have been tested in diesel engines [17]. Investigations were also performed on the use of heavy oil – water emulsions on an industrial scale [18,19].

Kumar et al. performed experiments in a diesel engine using waste cooking oil (WCO)/water emulsions and observed improvements in the brake thermal efficiency (BTE) at high power outputs but low BTE at low power outputs when compared to the base diesel fuel [5]. Lower smoke opacity than WCO but higher smoke opacity than diesel fuel was also observed. Hydrocarbon (HC) emissions varied with power output. At high power output, WCO emulsion had lower HC emissions than diesel but at low power output the opposite effect was observed. The same authors carried out additional experiments in a diesel engine using an emulsion of animal fat and water with ethanol [6]. They observed a decrease in smoke, $NO_x$, HC and CO when compared to pure animal fat and neat diesel at high power outputs. Animal fat emulsions were observed to have higher HC and CO emissions at light engine loads. A comprehensive review on the use of biofuel emulsions in diesel engines was also published [7]. A leading conclusion in the related works is that biofuel emulsions improved the combustion efficiency and performance with reduced $NO_x$ and PM emissions. Research work in Refs. [8–13] showed a reduction in $NO_x$, soot, HC and PM emissions, and an improvement of combustion efficiency for diesel-water emulsions. Alahmer et al. observed that as water content increased, BSFC increased at high engine speeds, BTE decreased, exhaust gas temperature (EGT) decreased, and $NO_x$ also decreased [10]. In the case of experiments by Zaid et al., an increase in water content resulted in an increase in BTE, an increase in BSFC (diesel and water considered as total fuel) and a decrease in EGT [12]. Cherng-Yuan et al. [14–16] carried out a series of studies with three-phase diesel emulsions in a diesel engine and indicated an increase in BSFC and CO with a decrease in $NO_x$, $CO_2$ and smoke opacity. Varying concentrations of diesel-ethanol emulsions were also tested in a diesel engine [17]. The results showed that as the volume of ethanol was reduced an increase in BTE, a decrease in specific fuel consumption and a decrease in $NO_x$ occurred. The general consensus from experiments carried out so far with emulsions in a diesel engine is that they lead to reduced $NO_x$ and smoke emissions. Yang et al. [20] performed experiments in a diesel using an emulsion of diesel, water, organic oxygenated additives and NP-9 surfactant. They observed an improvement in BTE, $NO_x$ and noticed a longer ignition delay for the emulsions. Chang et al. [21] used emulsions made of water containing acetone – butanol – ethanol and diesel fuel in the absence of a surfactant at different concentration in a diesel engine. From their work, they observed an increase in BTE and a decrease in PM, $NO_x$ and PAHs. Additional experiments carried out in a natural gas fueled engine using water in biodiesel emulsion [22] resulted in increased HC and CO emissions with very subtle changes in $NO_x$ emissions. Research carried out to study the effect of water concentration on cylinder head deposits [23] showed significant decrease in carbon and hydrogen deposits as water content in emulsions is increased.

Micro-explosion and puffing are the two most important phenomena attributed to emulsion combustion in a diesel engine. Micro-explosion is the quick break down of droplets, which results in secondary droplet atomization [24]. It occurs because water and oil have different boiling temperatures, which results in water evaporating much faster than the oil in a hot combustion chamber. In water-in-oil emulsions, water droplets are the dispersed phase, surrounded by oil. In a hot combustion chamber, the water droplets will reach superheating much faster than the oil thus resulting in micro-explosion. In the case of puffing, water leaves the oil droplets as a fine mist [4,24]. Not all researchers have, however, agreed on the occurrence of micro-explosions in diesel engines as was discussed by Weibiao et al. [8].

Most of the experiments carried out in diesel engines using fuel-water emulsions have typically used water as the dispersed phase with the oil (fuel) as the continuous phase. In this work, the opposite emulsion type was used, namely, oil-in-water emulsions that were formulated by using diesel, jet fuel and biodiesel as base fuels (emulsion oil phase). It should be noted that this is the first demonstration of the utilization of oil-in-water fuel emulsions in a diesel engine. Importantly, the stability of the emulsions was attained by incorporation of a modified technical lignin (carboxymethylated Kraft lignin), which acted as amphiphile molecule or polymeric surfactant. Therefore, the main objective of this work is to study the feasibility of oil-in-water emulsions stabilized by an inexpensive and widely available biomolecule as fuels for diesel engines.

## 2. Experimental

### 2.1. Fuels and fuel emulsions

Ultra-low sulfur diesel fuel (No. 2 diesel) was used in the experiments. It was obtained by blending diesel fuels acquired from three different gas stations at the same ratio by volume. Biodiesel was obtained locally from a biodiesel plant and it was produced from waste cooking oil. The biodiesel had a cetane number of 55.4. Jet fuel was purchased locally from a civil airport.

Industrial Kraft lignin with low ash content (0.5%) was kindly donated by Domtar Inc. (Plymouth Pulp Mill, NC). The lignin molecular weight was ca. 6200 Dalton and its methoxy group content was measured to be 11.5% (NMR). Elemental analysis