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The effect of fuel injection equipment on the dispersed phase of water-in-diesel emulsions

Mhadi A. Ismael[a,b,*], Morgan R. Heikal[a,c], A. Rashid A. Aziz[a], Firman Syah[a], Ezrann Z. Zainal A.[a], Cyril Crua[c]

[a] *Center for Automotive Research and Electric Mobility, Universiti Teknologi PETRONAS, Perak, Malaysia*
[b] *Mechanical Engineering Department, University of Bahri, Khartoum Bahri, Khartoum, Sudan*
[c] *Advanced Engineering Centre, University of Brighton, Brighton BN2 4GJ, United Kingdom*

HIGHLIGHTS

- We studied the effect of a common-rail injection system on water-in-diesel emulsion.
- Dispersed droplet sizes are significantly reduced by the high-pressure fuel pump.
- Dispersed droplet sizes are further reduced by the injector's nozzle orifices.
- Fuel returned to the tank by the pump and injector also had smaller dispersed phase.
- Properties of the emulsion in the fuel tank can change significantly with time.

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ABSTRACT

Water-in-diesel emulsions are known to lead to micro-explosions when exposed to high temperatures, thereby offering a technology that could improve the mixing of fuels with the ambient gas. The number and size distributions of the dispersed phase have a significant effect on both the long-term stability of the emulsion and the probability of micro-explosion inside an engine. Although the elevated pressures, temperatures, and shear found in high-pressure pumps and common-rail injector nozzles are likely to alter the properties of emulsions, the effect of these engine components on the injected emulsion are not known. To address this issue we sampled an emulsion at several locations within the injection system, from the fuel tank to the injector nozzle, and measured the evolution of the droplet size distribution of the emulsion's dispersed phase. We varied the water mass fraction (5, 10 and 15% by volume) of the emulsion and the injection pressure (500, 1000 and 1500 bar), imaged the samples using a high-resolution microscope and extracted the droplet size distribution using a purpose-built image processing algorithm. Our measurements reveal that the dispersed droplet sizes reduce significantly after the emulsion is compressed by the high-pressure fuel pump, and again after being injected through the nozzle's orifices. Additionally, the dispersed droplet sizes measured from the pump's return and injector return to the fuel tank were also smaller than the initial size, suggesting that the physical and calorific properties of the emulsion in the fuel tank can change significantly with time. Hence we propose that differences in injection equipment and engine testing duration may contribute to some of the disagreements in the literature regarding the effect of emulsified fuels on engine emissions and fuel efficiency. The engine performance and energy efficiency of vehicle fleets that use emulsified fuels will vary with engine running time, thus potentially inducing a drift in the engine performance and exhaust emissions. This investigation also suggests that, in order to be representative of actual injection conditions, fundamental studies of the micro-explosion of emulsion droplets should be performed using much smaller dispersed droplet sizes than those normally found in an unused emulsion.

1. Introduction

By combining high thermal efficiency and high energy density, diesel engines have dominated medium and heavy duty transportation. However, they remain a significant source of environmental pollution and a concern for air quality in urban areas. To mitigate these issues

* Corresponding author at: Center for Automotive Research and Electric Mobility, Universiti Teknologi PETRONAS, Perak, Malaysia.
E-mail address: mhadi_g03348@utp.edu.my (M.A. Ismael).

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and meet stringent emission regulations, engine manufacturers have used a range of hardware-based strategies, such as high-pressure fuel injection, particulate filters, exhaust gas recirculation, fast-response injectors and multiple injection strategies [1]. While these technologies have significantly reduced the tailpipe emissions of new modern vehicles, they remain both expensive and generally unsuitable for retrofitting on existing vehicle fleets. Hence there is a need to identify fuel-based technologies that could enable the production of clean low-cost heavy-duty powertrains, and provide a way to reduce emissions from existing vehicles, particularly for developing countries where the cost of state-of-the-art hardware technologies may be prohibitive.

Water-in-diesel emulsions have received significant attention due to their potential simultaneously reduce NOx and particulate emissions. However, despite evidence of some beneficial effects the technology needs more research to improve the emulsified fuels' stability and to better understand their interaction with the fuel injection hardware. Different methods have been implemented to introduce water into the engine cylinder, including through injection into the intake manifold [2], the direct injection of water into the combustion chamber [3,4] and the emulsification of water into diesel prior to injection into the chamber [5–13]. More recently the emulsification of diesel with water in real-time has demonstrated the possibility of producing on-board water-in-diesel emulsions without the need for surfactants [14,15]. Although a reduction of emissions was obtained using the water injection methods, the engine suffered from corrosion and required extensive modifications. Therefore the use of water-emulsified diesel fuel could be a more efficient approach for the reduction of exhaust emissions while improving engine performance, without requiring any engine modification. Diesel and biodiesel-diesel emulsions with 15% water concentration were found to increase break thermal efficiency by approximately 6%, with a 30% reduction in NOx and smoke and a 70% reduction in unburnt hydrocarbons [16]. Brake specific fuel consumption (BSFC) increases due to the lower calorific value of the emulsions [17] as water displaces diesel fuel. However, computing BSFC using the nominal water content of an emulsion neglects the possibility that the engine's fuel system could promote de-emulsification and the loss of water through heating and shearing of the emulsion. As a result, the actual proportion of water in the emulsion injected inside the engine cylinder could be lower than that of the "fresh" unused emulsion. If strictly the amount of fuel within the emulsion is considered to compute the BSFC then fuel consumption is found to reduce when compared to neat diesel [18]. Hence, a better understanding of the effect of the fuel injection hardware on the properties of the emulsions is essential if correct fuel efficiency calculations are to be performed.

Interestingly, some research shows that emulsifying diesel with wet algal biomass instead of water could produce reductions of NOx and particulate emissions while also increasing the calorific value of the emulsion [19]. An increase of water concentration to 30% results in longer ignition delays due to the lower volatility and higher viscosity of the dispersed phase [20]. The vaporization of the emulsion's water seems to reduce in-cylinder temperature, thereby reducing NOx formation [21,19]. Soot emissions also reduce through the increased formation of hydroxyl radicals when a water-in-diesel emulsions are subjected to high temperature, which increase the oxidization rate of the soot [22]. Research shows that effects of emulsions on NOx emissions [23] and engine efficiency [24] are significantly related to the properties of the dispersed water droplets, with smaller dispersed droplet sizes leading to improvements in combustion and emissions. Yang et al. [9] argued that smaller dispersed water droplet sizes accelerate flame propagation and therefore shorten the combustion duration. There is also some speculation in the literature that the combustion process is also improved through an increased secondary atomization [25,26], leading to better air-fuel mixing [27]. The potential for water-in-diesel emulsions improving the secondary atomization process is believed to be attributed to the phenomena of puffing and micro-explosion. Micro-explosion is caused by the rapid breakup of a droplet due to the different volatility of the diesel (continuous phase) and water (dispersed phase), leading to the accelerated breakup of the emulsion droplets into smaller droplets. The puffing phenomenon is related to some of the dispersed water bursting out of the emulsion droplets [28]. Both phenomena enhance the effective fuel droplet size distribution, air-fuel mixing, and ultimately the fuel efficiency [29]. The speculation that micro-explosion and puffing improve secondary atomization and combustion in engines [30] seem mostly based on indirect evidence that increased spray dispersion angle and penetration [25] result in longer ignition delay, which in turn enhances the air-fuel mixing [9,32]. Despite these findings only few studies provide direct observations of droplet micro-explosions in conventional sprays [31,33–35] and during combustion [36,37].

Micro-explosion is a particularly fast process which cannot be captured easily at engine operating conditions. Hence, single droplet experiments are often used to facilitate the observation of these events and to develop hypotheses on the relation with the performance of emulsions in engines [38–40]. Observations of the occurrence of micro-explosion for isolated emulsion droplets showed that these events are influenced by water concentration, surfactant type, dispersed water droplets size and temperature [41,42]. Some researchers observed that the intensity of micro-explosions increased with water content [43,44] as well as with the droplet size of the dispersed water phase. Fine dispersed droplets (1–2 μm diameter) did not give rise to micro-explosion [45], and the optimum dispersed droplet size was found to be in the order of 5 μm [46]. The reason for fine dispersed water droplets to inhibit or delay micro-explosion is believed to be due to their lower coalescence rate [42,47]. A particular limitation of these direct observation of micro-explosion events is that the size of the isolated emulsion droplets tend to be several orders of magnitude larger than the droplets found in typical diesel sprays.

The size of the dispersed water droplets is a good indicator of de-emulsification, hence it can play significant role in improving our understanding of the emulsion properties and its evolution through the fuel injection system. Therefore, to control the micro-explosion and energy efficiency of emulsified fuels it is essential to control the number and size distributions of the dispersed phase from the tank through to the injector. These characteristics are highly dependent upon the water concentration in the emulsion [48], as well as the emulsion production method. For example using a mechanical stirrer (average droplet size ∼30 μm), decreases breakup rate and increases coalescence rate resulting in larger droplet sizes [45,49]. While using a homogenizer (average droplet size ∼2 μm), the emulsions are subjected to intense pressures, temperatures and shear flow fields, therefore, the coalescence rate was found to be even higher with increased water evaporation before injection in the engine [50].

Recent theoretical models for the mixing characteristics of water-in-diesel emulsions have demonstrated the importance of the emulsion's density [51], the temperature distribution of the continuous phase [52], and the size distribution of the dispersed phase [28]. However, direct evidence of the impact of the fuel injection system on the dispersed phase has been sorely missing, despite the significant pressures, temperatures and shear imposed on the fuel by several hardware components. Improving our understanding of the evolution of the emulsion's properties throughout the fuel injection equipment (FIE) is essential for the validation of numerical simulations of in-cylinder micro-explosion of water-in-diesel fuels.

In this article we address some of these limitations, and show that both the high-pressure pump and injector nozzle significantly modify the size distribution of the dispersed phase. We show that the high-pressure pump shifts the dispersed water droplets to a smaller mean diameter (Section 3.1). Hence the fuel that is returned to the fuel tank (from the pump, common-rail and injector returns) is different from the initial emulsified blend, thus inducing a progressive change of the physical and calorific properties of the fuel in the vehicle's tank. We also show that the injector nozzle further shifts the dispersed water