DIESEL-WATER EMULSION, AN ALTERNATIVE FUEL TO REDUCE DIESEL ENGINE EMISSIONS. A REVIEW

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Abstract: *Oxides of nitrogen (NOx) and particulate matter (PM) are the main pollutants from diesel engines. Diesel-water emulsion, as alternative fuel, has potential to significantly reduce the formation of NOx and PM in the diesel engine. The emulsion fuel contains water (in the range of 5–15%) and diesel fuel with specific surfactants, to stabilize the system.*
Reduction of NOx is originated from the reduction of local high temperature due to vaporized water during combustion. The reduction of local high temperature may cause the reduction of reaction rate, which has a possibility of affording a mixing time for better combustion for reducing PM. Micro-explosion, considered as the second atomization, improves fuel combustion and reduces fuel consumption.
The heterogeneous results regarding the use of diesel-water emulsion as fuel for diesel engines suggest that experimental work for optimizing the emulsion formulation in terms of water content and internal structure is recommended.

Keywords: diesel engine, diesel-water emulsion, micro-explosion, NO_x emission, PM emission

1. Introduction

The use of water in diesel engines has a number of possible benefits [1]. It has been found that it has an influence on reducing the peak flame temperature and hence reducing the NOx emissions.

The technique concerned with introducing water into engine combustion chamber was proposed by Prof. B. Hopkinson in 1913, to make better internal cooling of the gas engine and to increase the engine output [2]. Furthermore, the technique was developed to improve the thermal efficiency and reduce exhaust emissions, or used as the safety fuel.

Four major approaches for introducing water into the combustion zone have been reported in the literature [1-7]: (i) Direct injection into the engine through separate injectors (DWSI); (ii) Hybrid injection, using a single injector or as a stratified diesel-water-diesel fuel injection by means of a specially modified nozzle (HDWI); (iii) Fumigating the water into the engine intake air (FWIA); (iv) Diesel-water emulsions (DWE). Of all the methods proposed to introduce water into the combustion chamber, diesel oil emulsions appear to be the most appropriate, because they require no engine retrofitting [4]. A comparison of the four methods of water addition in diesel engine vs. some technical and economical criteria is presented in Table 1.

Table 1. *Comparison of water addition methods [6].*

	DWSI	HDWI	FWIA	DWE
Relative NOx reduction	Poor	Best	Poor	Good
Effect on PM emissions	Poor	Best	Poor	Good
Variability of water addition	Good	Poor	Good	Good
Lubricating oil dilution	High	Low	High	Low
Expenditure	High	Average	Low	High

Although all these methods determined a reduction of NOx emission, it has been concluded that the use of diesel-water emulsion was the most effective technique for the reduction of diesel particulates for direct injection diesel engines [8]. It has also been shown that adding water may help to improve atomization and mixing, which is attributed to emulsion droplet micro-explosions [1].

Since diesel-water emulsion has a potential in reducing NOx and PM emissions of diesel engines, this paper presents a literature review on emulsion significant aspects that determined its use in diesel engines and its influence on diesel engine performance.

2. Diesel-water emulsion

An emulsion consists of two incomplete immiscible liquids (usually oil and water), with one of the liquids dispersed as small spherical droplets in the other [9,10]. According to [11], an emulsion is a two-phase liquid system consisting of fairly coarse dispersions of one liquid in another in the form of droplets, whose diameter exceeds 0.1 microns. In an emulsion, the droplets of one phase (the dispersed or internal phase) are encapsulated within sheets of another phase (continuous or external phase) [12]. The essential characteristics of an emulsion is its droplet size distribution [10].

Although emulsions have found numerous and various applications in chemical, pharmaceutical and food industries [9,10,12], emulsions of water in diesel fuel are easily applicable alternative fuels for the existing diesel engines [13]. The emulsion fuels contain water and standard diesel fuel with specific additives, surfactants, to stabilize the system [12,13].

Generally there exist two distinct diesel-water emulsion types, water-in-oil and oil-in-water type [11]. Water-in-oil type is best suited type of fuel for diesel engines rather than oil-in-water type due to the micro-explosion phenomenon of droplet of water, which causes a large fragmentation of the oil and less change in viscosity with water content.

A surfactant can reduce the oil and water surface tension, activate their surfaces, and maximize their superficial contact areas to make oil-in-water or water-in-oil two-phase emulsions [14]. Surfactants or surface-active agents are amphipathic substances with lyophobic and lyophilic groups making them capable of adsorbing at the interfaces between liquids, solids and gases [12]. A surfactant is also called an emulsification agent because it can stabilize emulsions when it exists along the interface between water and oil [14]. In diesel-water emulsion, the surfactant suspends the water droplets in the fuel, thus the water does not come into direct contact with engine surfaces [4]. The additives are included to maintain the emulsion, enhance the lubricity, inhibit corrosion and protect against freezing [15].

3. Types of diesel-water emulsions

In general, oil-water emulsions can be conveniently classified according to the relative spatial distribution of the oil and aqueous phases [9]. A system that consists of water droplets dispersed in an oil phase is called a water-in-oil or W/O emulsion (fig. 1), and a

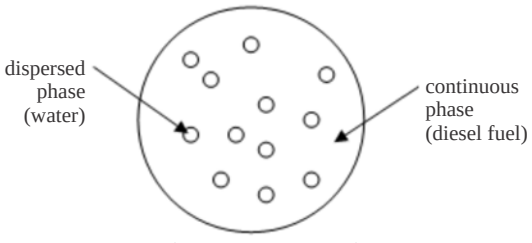

Fig. 1 *Illustration of physical structure of a W/O emulsion [17].*

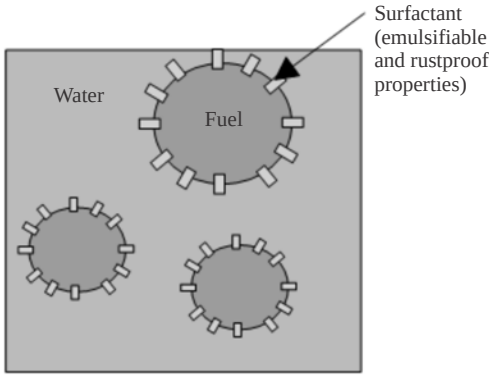

Fig. 2 *Illustration of a O/W emulsion fuel, containing 50% water [18].*

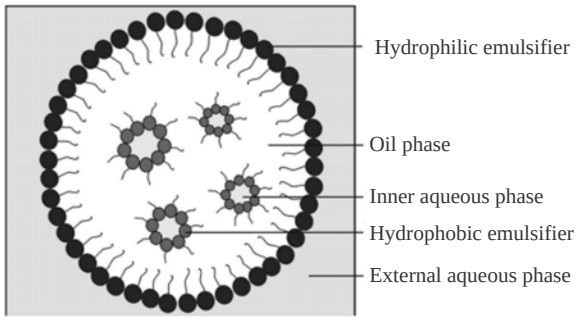

Fig. 3 *Schematic representation of a W/O/W multiple emulsions [19].*

system that consists of oil droplets dispersed in an aqueous phase is called an oil-in-water or O/W emulsion (fig. 2) [9,11,16,17]. Multiple emulsions are composed of three phases: an inner and an outer phase separated by a dispersed phase [16]. Three-phase emulsions [16] or double emulsions [13] are denoted as: O/W/O (oil-in-water-in oil) [13,16] and W/O/W (water-in-oil-in-water) (fig. 3) [16,19].

Diesel-water emulsions can be classified according to the size of drops in the emulsion. The size of the drops in an emulsion are in the range of 1-10 μm [20], while in a micro-emulsion are much smaller, e.g. 5-20 nm [20] or less than 0.2 μm [6]. It is believed that high-quality combustion can be achieved with an average size of the water particles dispersed in the liquid fuel of generally less than 1.5 microns, preferably between 0.05 and 1 microns [11]. Nano-emulsions consist of very small emulsion droplets, commonly oil droplets in water, exhibiting sizes lower than ~300 nm [21].

Emulsions and micro-emulsions differ not only in the size of the drops of the dispersed phase, but also in terms of their thermodynamic stability [20]. Micro-emulsions are thermodynamically stable [20], meanwhile emulsions are thermodynamically unstable [20,22] and will separate into two phases in due time, although this separation can be delayed by a careful choice of surfactants and polymers [20]. However, the thermodynamic stability of the micro-emulsion do not compensate for the drawback of the much higher loading of surfactants needed in a micro-emulsion formulation compared to an emulsion formulation [13]. The micro-emulsion route is probably too costly for a very large scale application, such as fuels for vehicles.

4. Emulsion characteristics

Stability

Among emulsion characteristics, the stability has great importance [23]. The stability depends mainly on the type and quantity of surfactant that is used in the emulsion formulation [23], through the mode on how the surfactants adsorb to the newly created interfacial area [24].

As soon as the emulsion is formed, it starts to change due to several time-dependent processes, among which creaming, sedimentation, Ostwald ripening, flocculation, and coalescence appear to be the most important [24,25].

The main criterion for a stable emulsion is the presence of only one phase [26]. If more than one layer is found, it must be considered to be an unstable emulsion. Parameters that affect the separation of liquid-liquid dispersion suspension are [27]:

a. drop size and its distribution in continuous phase;
b. drop motion in the dispersions, drop coalescence, into their phases and binary coalescence between drops;
c. existence of different dispersion types, oil in water, water in oil, or a combination of both;
d. geometry, that is, diameter of the settling tube, height of the initial dispersion band, and insertions in the separation volume;
e. existence of solid or gas phase in the dispersion.

Figure 4 presents the variation of sedimentation zones and coalescing interfaces in a diesel-water emulsion.

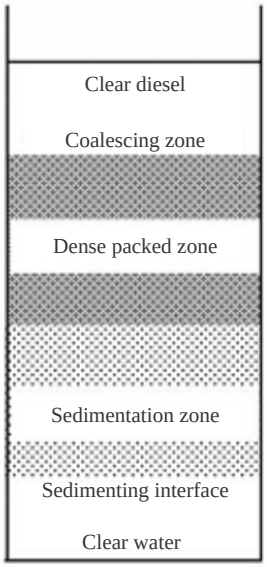

Fig. 4 *Variation of sedimentation zones and coalescing interfaces in a diesel-water emulsion [27].*

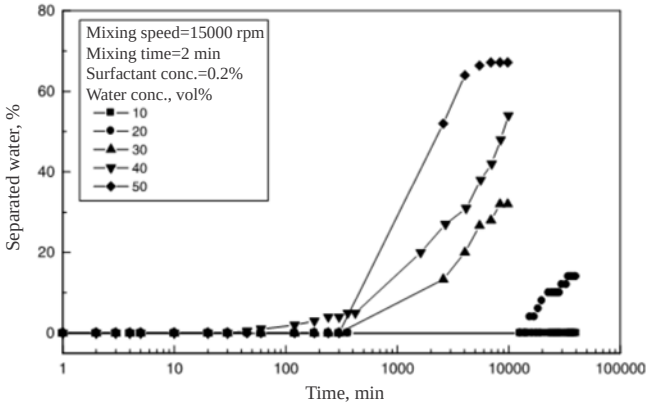

Fig. 5 *Stability profile of a water-in-diesel emulsion for different water content [26].*

In [26] the stability of water-in-diesel emulsion versus water concentration, surfactant concentration, mixing speed and time was investigated. For a given surfactant concentration and mixing speed and time, the percentage of separated water gradually increased with the water concentration (fig. 5).

Viscosity

Viscosity is an important property of diesel fuel, which effects fuel combustion performance [28]. The less the fuel viscosity, the better the fuel fluidity, which improves fuel atomized property so as to decrease fuel consumption and pollutant emission.

In general, water-fuel emulsions exhibit greater viscosity than

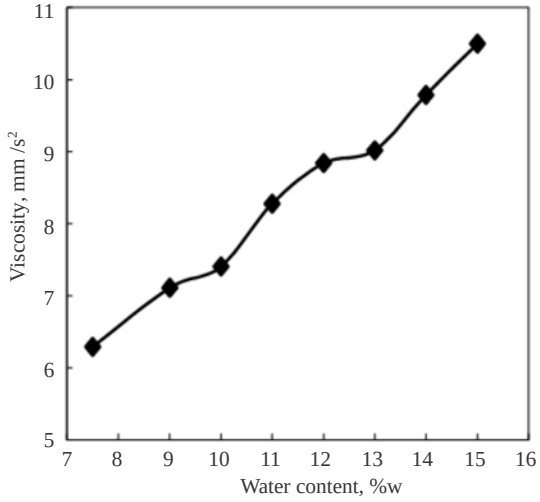

Fig. 6 *Effect of the water content on the viscosity of a micro-emulsion diesel oil [28].*

pure liquid fuels, and both water content and size of the droplets dispersed in the emulsion significantly influence its viscosity (fig. 6) [29].

Heating value

In general, torque and power produced by emulsified fuels are lower as compared to the neat diesel fuel due to the lower heating values for emulsified fuels [12,30,31]. The effect of water content in diesel-water emulsion on the low heating value of the emulsion is presented in figure 7.

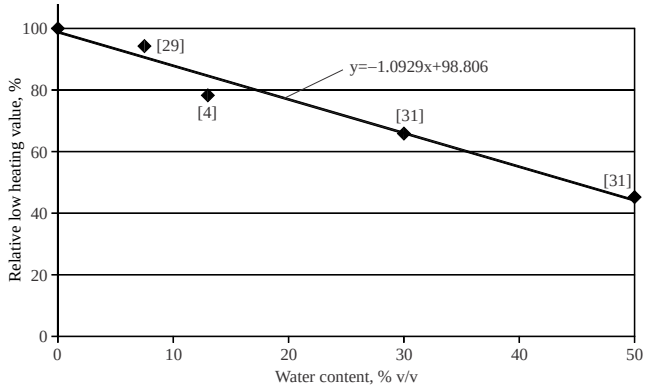

Fig. 7 *Reduction of relative low heating value versus water content in emulsion.*

5. Performance of diesel engine fueled with diesel-water emulsion

In literature there exist a relative large number of papers dealing with tests performed on diesel engines fueled with diesel-water emulsions, in order to determine how this emulsion fuel influences the engine performance as: power (torque), fuel consumption, NOx and PM/soot/smoke emissions. A synthesis of four papers is presented in table 2.

Analysis of data from table 2 reveals both convergent and divergent results. In general, engine power (torque) decreases with water content, due to lower heating value of emulsion compared to pure diesel fuel. Fuel consumption is increasing due to the same reason.

On the other hand, diesel-water emulsion leads to a reduction of NOx and PM emissions. Differences between emission results, sometimes in a significant degree, may be caused by: engine (compression ratio, fuel system), emulsion (type of emulsion, water content, surfactant type and content, emulsion preparation) and test conditions (engine load, speed and injection timing).

Table 2. *Influence of diesel-water emulsion on diesel engine performance.*

Engine type and test conditions	Emulsion W/O (%v/v)	Power/ torque	Fuel consum-ption	NOx	PM/ Soot	Ref.
Isuzu, 4 cyl, 3856 cm^3, ε=17 65.6 kW @ 2800 rpm	10 and 20% Surf.: 2%	NA	+	–	–	[14]
Ford, 4 cyl, 1753 cm^3, ε=21,5 44.7 kW @ 4800 rpm	5, 10 and 15% Surf.: 0,2-1,0%	–	+	– –	– –	[12]
4 buses Euro 2, (2 old and 2 new)	13,5% Surf.: NA	NA	+	+ & –	–	[33]
Engine of 6 cyl, 11149 cm^3, ε=16,4	15% Surf.: NA	–	+	–	–	[34]

Symbols: ε-compression ratio; + increasing, but in less degree; + + increasing, but in significant degree; – reduction, but in less degree; – – reduction, but in significant degree; NA-not available data

According to the engine test results both NOx and smoke tend to decrease as the emulsion ratio increases [35]. The lower peak temperature in cylinder due to the water content in emulsion fuel accounts for lower NOx [4,35], while enhanced mixing with air by micro-explosions accounts for lower smoke emission [35].

6. Conclusion

Diesel-water emulsion has a potential in reducing NOx and PM emissions of diesel engines.

Water-in-oil emulsion is best suited type of fuel for diesel engines rather than oil-in-water type due to the micro-explosion phenomenon of droplet of water, which causes a large fragmentation of the oil and less change in viscosity with water content.

In general, engine power decreases with water content, due to lower heating value of emulsion compared to pure diesel fuel.

NOx and smoke emissions tend to decrease as the emulsion ratio increases due to the lower peak temperature in cylinder due to the water content in emulsion fuel and enhanced mixing with air by micro-explosions.

The heterogeneous results regarding the use of diesel-water emulsion as fuel for diesel engines suggest that experimental work for optimizing the emulsion formulation in terms of water content and internal structure is recommended.

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