Fuel 116 (2014) 703–708

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Influence of the structure of water-in-fuel emulsion on diesel engine performance

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HIGHLIGHTS

- Viscosity of emulsified fuel depends on both water content and emulsion structure.
- The emulsion structure affects engine mechanical and environmental performance.
- Emulsified fuel with finer droplets has a better effect on engine performance.
- Membrane emulsification is successfully used to regulate the emulsion structure.

ARTICLE INFO

Article history:
Received 1 June 2013
Received in revised form 19 August 2013
Accepted 20 August 2013
Available online 2 September 2013

Keywords:
Diesel engine
Exhaust gas emissions
Water-in-Fuel Emulsion (WFE)
Emulsion structure
Membrane emulsification

ABSTRACT

In this work the effect of the structure of water-in-diesel fuel emulsion (WFE) on a three cylinder diesel engine performance has been investigated. Based on membrane emulsification, two different membranes of pore sizes of 0.2 μm and 0.45 μm has been individually used to change the emulsion structure while keeping the same WFE volumetric content (at 17% water volumetric content and 0.5% mixing emulsifier content). The Results showed that emulsions with large size of water droplets resulted in greater reduction in NO_x emissions up to 25%. While, emulsions with finer droplets not only gave reductions in engine smoke and unburned hydrocarbons of values greater than 80% and 35% respectively, but also resulted in an increase of the engine effective efficiency up to 20%.

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1. Introduction

Current limitations of fuel resources and restrictions on environmental pollution have directed research programs worldwide to introduce new techniques and methodologies that not only ensure rationalization of fuel consumption but also keep emissions at ultra-low levels from different combustion devices. Particular attention is certainly given to both petrol and diesel engines as they represent a major contributor to both fuel consumption and environmental pollution. Alternative fuels including biodiesels as well as the use of fuel additives are among recent methodologies that aim at better utilization of low calorific fuels and/or improving engine performance while meeting environmental regulations. The mixing of low calorific fuels with light fuels and/or the use fuel emulsions (fuel mixed with water) are currently considered as promising ways to realize improved fuel economics and usage of low grade fuels.

The use of Water-in-Fuel Emulsion (WFE) has been stated as the most universal and effective method that enable simultaneous reduction of the engine smoke level and nitrogen oxides (NO_x) without the necessity for engine modifications [1]. The introduction of water within the fuel has two contradicting effects:

(i) It worsens the engine efficiency as due to the higher energy needed for water evaporation (larger than 10 times that for diesel fuel evaporation) as well as the reduction of the fuel calorific value.
(ii) The improvement of engine emissions with possibility to improve the base fuel economics as due to the enhancement of fuel atomization resulting from the occurrence of micro-explosion [2] (water evaporates at 100 °C causing expansion that exceeds the interfacial tension between fuel and water vapor); leading to better fuel–air mixing [3].

The general effect of WFE on the fuel properties and the engine combustion can be summarized as:

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0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.08.057

(1) The reduction of spray angle with the increase of water content due to viscosity increase [4]; resulting in worsening the fuel evaporation. However, the improvement of fuel evaporation due to the effect of secondary atomization far exceeds such degradation.
(2) The increase of ignition delay period with the increase of water content whatever the fuel type [4]. This leads to larger part of premixed combustion as compared to the subsequent diffusion combustion. This leads to: (i) higher rate of pressure rise within the engine cylinder [5], (ii) increase of engine indicated thermal efficiency [6–8], (iii) reduction of thermal stresses of the engine components especially during cold engine operation and (iv) reduced wear rate [6].
(3) The reduction of the emulsified fuel combustion duration or the reduction of emulsified droplet lifetime (especially for heavy fuels, where the possibility of micro-explosion occurrence is higher) [6,9]. Thus the flame height is reduced and become more intense around its axis [10]. This behavior is continued up to volumetric water content of 30% [4].
(4) The increase of the local excess air factor as due to greater air aspiration caused by the movement of droplets of larger density and viscosity [11]. This leads to a remarkable reduction of local temperature and so the NO_x emissions are decreased. Moreover the increase of local air contents will accelerate the soot oxidation [11,12].
(5) The increase of the injected emulsified fuel volume to maintain the same engine power. This additionally necessitates an increase of the injection duration; leading to the continuation of the combustion process during the expansion stroke giving insufficient time for soot oxidation. Thus, soot emission will increase [9].

It can be noted that, the use of WFE has a remarkable effect on the reduction of NO_x and smoke levels, however there is a debate about its effect on carbon monoxide (CO) and unburned hydrocarbons (C_nH_m) emissions [13]. The effect of WFE on CO emission will mainly depend on engine load and the compromise between the viscosity increase and the local temperature decrease [14]. At low and medium engine loads, CO concentration tends to increase as water content increase due to viscosity increase and the local temperature decrease. But at full load there is a tendency to reduce CO emissions due to the increase of temperature (advances in the micro-explosion) that exceeds the effect of viscosity. Moreover, the volumetric water content (Φ) plays a major role on the effect of WFE on CO emissions; for $\Phi > 30\%$ CO emissions will increase [16], for Φ of order 20–25% there will be a slight effect, and for $\Phi < 20\%$ CO emissions will decrease [15]. Since emissions of C_nH_m are formed at conditions of lean mixture and poor fuel atomization, the use of WFE has a greater tendency to increase its level especially at low engine loads [5], but at medium and full loads (where combustion is fully developed) there is a slight tendency to decrease [14].

Many investigators studied experimentally conditions and characteristics of micro-expansion occurrence during the combustion of a single suspended emulsified fuel droplet within a constant volume combustion chamber [3,10,17–21]. However, during the combustion of emulsified fuel within the engine cylinder there is no unique fact about the occurrence of micro-explosions [1,13,22,23]. Novikov et al. [1] stated another reason for atomization enhancement of emulsified fuel related to the viscosity increase and the larger fuel quantity required to maintain the same engine power that lead to the increase of the fuel jet velocity with formation of larger droplets during the spay breakup. In this case, emulsified droplets will have greater ability to impinge over the cylinder wall, breaking into minor particles that spread rapidly within the cylinder volume (secondary atomization) providing better mixing conditions of fuel with air and increasing the part of premixed combustion mode. Mura et al. [3] found that, the reduction of water droplet size improve the atomization efficiency since the evolution of micro-explosion occurs very rapid. Moreover, the occurrence of group micro-explosions has been observed in eddy scale near the outer layer of emulsion spray ejecting fragments of finer droplets away from the spray boundary leading to rapid evaporation and great expansion of the spray zone [24].

The introduction of water into fuel has two main effects; (i) a physical impact as a fuel spray regulator increasing the premixed combustion mode and (ii) a chemical effect as a result of thermal dissociation of water at high temperature into active radicals (in particular hydroxyl $-OH^-$ and hydrogen $-H^+$) which accelerate the oxidation of incomplete combustion products, such as particulate matter (PM), C_nH_m, and CO [12,25,26]. Moreover, the interaction between soot and hydrocarbons with water vapor leads to the formation of molecular hydrogen (H_2) [12]. In this case there is a global positive environmental effect; the decrease of local temperature (due to energy losses consumed for water evaporation and dissociation) leads to a remarkable reduction of NO_x and the existence of active radicals leads to oxidation of CO and soot. In this way the use of WFE has a favorable impact on the soot/NO_x trade-off.

In the literature, the effect of WFE on engine performance has been widely studied depending mainly on the water content and engine operating conditions [1,4,8,13,26–29]. However, the analysis of these works and many others did not show a high degree of reproducibility or consistency about the effects of WFE on engine performance. This indicates that, there are additional factors that are not considered during these studies. One major factor that is rarely studied during the use of WFE in engines is the emulsion structure that is described in terms of (i) the size distribution of water droplets and (ii) the average diameter of water droplets within emulsion. The former determines the degree of homogeneity or dispersion coefficient of emulsion influencing its physical properties, while the later determines the interfacial area between water and fuel and characterizes the evaporation of water during heat transfer, and so affects the mixing of WFE with oxidizer. It is considered that the water droplet size within emulsion is an important factor being affected by the emulsion preparation and hence it is possible to get different emulsion characteristics even when the composition is fixed [30].

The emulsification process is the process of dispersing one liquid in the form of fine droplets (dispersed phase) into another immiscible liquid (dispersed medium) in the presence of a surface active substance (surfactant or emulsifier). The major challenges of emulsification process are the emulsion characteristics and the emulsion stability (how long until the two liquids partially or fully separated). The emulsion instability leads to changes of emulsion properties [31]. The first challenge depends on the emulsion preparation method or the technology used to deform the dispersed phase into fine droplets, while the second is solved or retarded by the proper selection of the type and concentration of emulsifier to reduce the interfacial tension between two immiscible liquids. There are many methods used for emulsification according to the required energy to deform liquid, the continuity of service and the force type [32]. However, there are limited number of systems that are capable of producing homogenous and fine emulsions as high pressure homogenizers and ultra-sound systems. Beside the high pressure or high energy needed to deform the dispersed phase, it is not easy to regulate the emulsion structure at fixed composition. This problem can be solved by using the membrane technology (micro-pore or micro-channel) that was introduced in 1988 [33]. In this method the dispersed phase (as water for WFE) is introduced under low pressure (just above the capillary value)

throughout pores of membrane forming spheres on the other side that can be separated from the surface by viscous force of the dispersed medium (fuel for WFE) flowing over the membrane surface; more details are found in [33,34].

In many investigations, the effect of droplet size of dispersed phase on the emulsion characteristics is studied by mixing different portions from two mono-dispersed emulsions [35,36]. The authors themselves [36] stated that using this methodology for preparation of different mono-dispersed emulsions of different mean size is impossible. On the other hand, using the membrane emulsification is confirmed to produce mono-dispersed emulsions [34,37,38]. In this way, changing the pore size of membrane will lead to the preparation of emulsion with different droplet mean size at fixed (or without worsening) size distribution. The degree of homogeneity is expressed by the dispersion coefficient (δ) defined as the size span between the particle size up to which the cumulative number percentage of particles is 90% (D_{90}) and that size corresponding to cumulative number percentage of 10% (D_{10}) related to the mean particle size (D_{50}) [37]:

$$\delta = (D_{90} - D_{10})/D_{50}$$

The smaller the value of the dispersion coefficient, the better the homogeneity of emulsion and the narrower the size distribution; for $\delta < 0.4$ the emulsion is considered as mono-dispersed emulsion.

Suitable emulsifier is needed to keep the emulsion structure stable for longer time without coalescence. Moreover, for engine applications it is recommended to use emulsifier having in their composition no emission resources as nitrogen, sulfur, and aromatic rings [39]. The emulsifier has the ability to dissolve with oil (lipophilic or hydrophobic) and water (hydrophilic) with different degree of solubility expressed by the hydrophilic–lipophilic balance (HLB). The suitable value of HLB for WFE is found to be in the range from 3 to 8. The most popular emulsifiers used for water-in-oil emulsification (as WFE) are those based on aliphatic hydrocarbons as sorbitan esters (known as span's and having HLB < 5). While for oil-in-water emulsifications, emulsifiers based on polysorbitan esters (known as tween's and having HLB > 14) are used. It is found that the use of mixtures from span's and tween's leads to better results, even than the use of a single surfactant with equivalent value of HLB [30,40].

The major objective of the current work is to study the effect of emulsion structure on diesel engine performance. This objective is achieved by performing the following steps:

1. Preparation of identical water-in-fuel emulsions with different structures. Throughout this step the membrane emulsification is selected to regulate the emulsion structure.
2. Examining the effect of emulsion structure on its properties.
3. Testing the engine performance at different operating conditions while running on the previously prepared mixtures.

2. Materials and method

The preparation of WFE has been realized by using the experimental setup of scheme shown in Fig. 1. The setup is based on the membrane emulsification using cylindrical ceramic membrane of inner diameter 6 mm, outer diameter of 10 mm, length of 22 cm, porosity of 50%, and pore size of 0.2 μm (or 0.45 μm). For improving of emulsion stability, mixing emulsifier from span'80 and tween'60 was added (0.5% by volume). In this case, each emulsifier was added to the corresponding soluble with concentration of 0.5%, i.e. tween'60 (HLB = 14.9) was added to water and span'80 (HLB = 4.3) was added to diesel fuel in this case the mean value of HLB = 9.2. Because the membrane material is hydrophilic, the membrane is firstly immersed in diesel fuel (including span'80) and allowed to dry using compressed air before water is introduced. The previous step has been recommended (immersing membrane within a hydrophilic reagents, it was easy to use diesel fuel) to prevent the formation of water film due to the low separation of neighboring water droplets from the hydrophilic surface [41]. All experiments were performed at laminar flow of diesel fuel within the cylindrical membrane (Reynold's number did not exceed 800). The prepared emulsion has been characterized visually with the help of optical microscope Micromed 3 (version 3–20) with digital camera DCM-510 to capture the emulsion structure and the dynamic light scattering system Horiba LB-550 to get the water droplet size distribution.

The experiments on engine have been performed using turbocharged three-cylinder diesel engine (cylinder diameter is 105 mm, and the piston stroke is 120 mm with compression ratio of 15) installed on engine test facility SAK-H-670. The basic instrumentations include fuel flow meter (AVL-730), air flow meter (RG-400), exhaust gas analyzer (AVL DiCom-4000) and smoke meter (AVL 415S). The tests were conducted without any engine modifications (except removing of the fine fuel filter to ensure that water droplets are not removed). The tests were performed according to standard of GOST R-41.96-2005 (equivalent to EC No. 96-01).

The engine runs on diesel fuel and on other two identical samples of WFE (with volumetric water concentration of 17% and mixing emulsifier concentration of 0.5%) prepared with the help of two membranes (one has pore size of 0.2 μm while the other of 0.45 μm) with mixing conditions according to Table 1.

3. Results and discussion

At the first step of this work a series of experiments to understand the effect of water concentration on the emulsion properties, especially emulsion viscosity, has been performed. During this step of the work, a solid emulsifier span'60 (HLB = 4.7) is mixed with tween'60 to stabilize the received emulsions. Since span'60 is solid substance, it was necessary to pre-heat a mixture of diesel fuel and the pre-defined quantity of span'60 up to fully melting of span'60 with diesel fuel (50–57 °C), then the mixture was cooled to the normal temperature before mixing with water at normal temperature. Even the emulsions stabilized by span'60 with tween'60 have better stability (more than one month), the formation of a condensed monolayers from span'60 and water may have problems to the engine fuel system, so another mixing emulsifier has been used for emulsion supplied to engine. The necessity for heating and the formation of condensed monolayers agree with those found by other investigators [42,43].

In this stage of the work, different emulsions with volumetric water concentration up to 50% were prepared using of membrane of pore size 0.2 μm. The results of size distribution confirm the change of particle size with negligible change of the dispersion coefficient, and so the size distribution is considered to be only shifted (Fig. 2 shows the size concentration and the percentage of cumulative size defined by undersize percentage). Even the fuel flow is laminar; the size distribution is symmetric (normal distribution) [44]. It is expected to get mono-disperse distribution at high fuel flow turbulence (for Reynold's number higher than 5000 [38]).

The measurements of emulsion viscosity (as a major property affecting fuel system, spray structure, and the air–fuel mixing process within diesel engine combustion chamber) are shown in Fig. 3. As water concentration increases, the emulsion viscosity increases. This effect is described by the flow pattern distortion of liquid layers due to the presence of another immiscible liquid droplets having size exceeding the liquid molecular size, thus the hydrody-

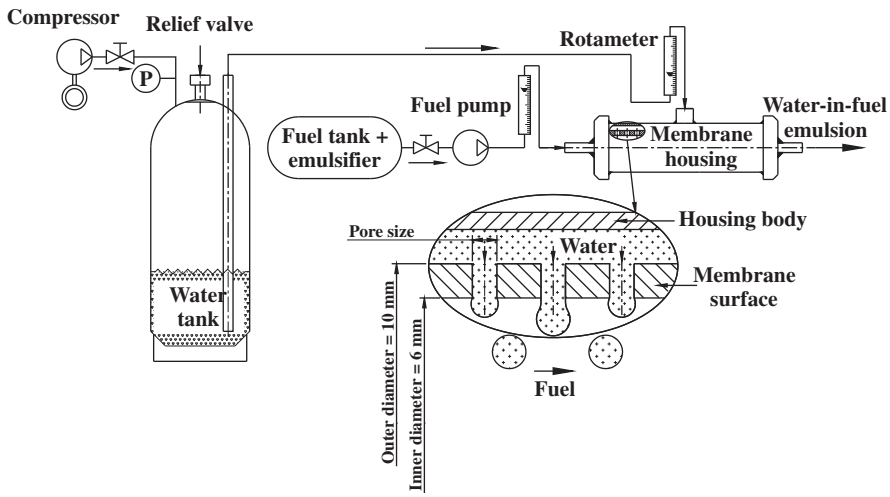

Fig. 1. The experimental setup for emulsion preparation based on membrane emulsification.

Table 1
Engine experimental conditions working on WFE based on fuel, engine speed, and engine power.

Fuel	N (rpm)	Engine power (kW)
• Diesel fuel (**DF**)	1500	15–30
• **WFE-0.2** (79.75% DF + 19.75% H_2O + 0.5% mixing emulsifier – emulsion prepared with membrane of pore 0.2 μm)	2000	3–35
• **WFE-0.45** (79.75% DF + 19.75% H_2O + 0.5% mixing emulsifier – emulsion prepared with membrane of pore 0.45 μm)		

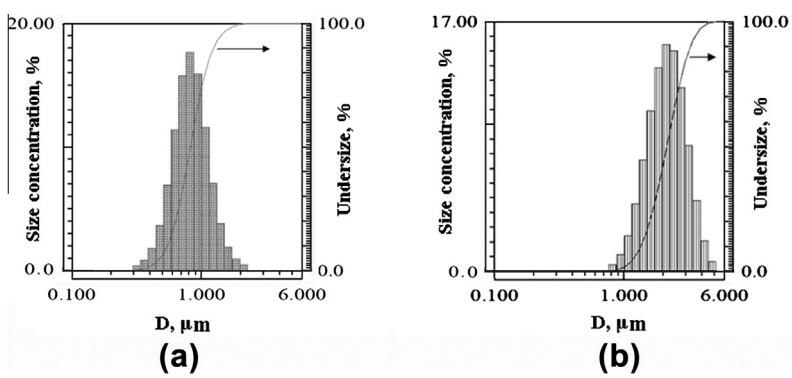

Fig. 2. Water droplet size distribution within the WFE stabilized by span'60 with tween'60 and measured after preparation by 10 days using membrane of 0.2 μm pore size. (a) For water concentration of 21%, D_{90} = 1.3 μm, D_{50} = 0.82 μm, D_{10} = 0.55 μm, $\delta \approx 0.91$, and (b) water concentration of 35%, D_{90} = 3.4 μm, D_{50} = 2.14 μm, D_{10} = 1.41 μm, $\delta \approx 0.93$.

namic interaction between water droplets in the fuel will increase the coefficient of internal friction of emulsion [44].

Another major parameter affecting the emulsion viscosity is the droplet size. In this work identical samples of emulsions were

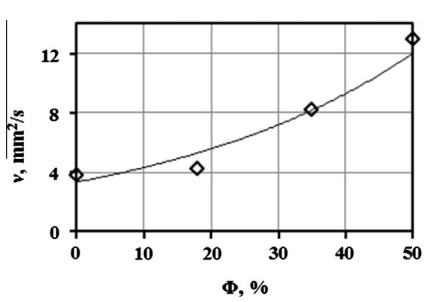

Fig. 3. The change of emulsion viscosity (ν) as a function of volumetric water concentration (Φ). Measurements were performed with the help of capillary viscometer having capillary tube diameter of 0.56 mm at temperature of 18 °C.

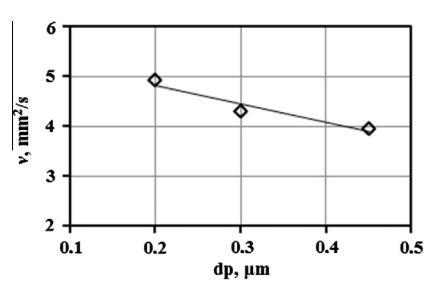

Fig. 4. The change of emulsion viscosity (ν) of WFE stabilized by span'80 with tween'60 due to change of membrane pore size (d_p) measured by capillary viscometer (capillary diameter of 0.56 mm). Viscosity measurements are performed at 22 °C after month of the preparation process.

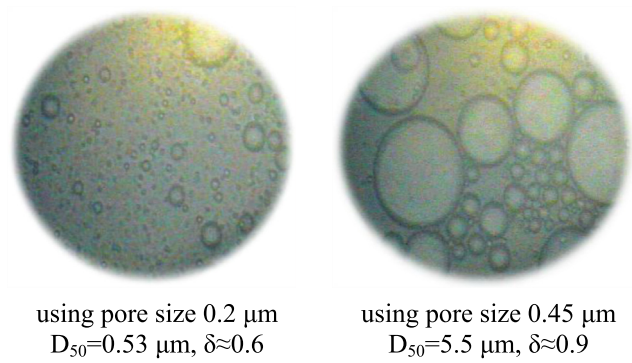

Fig. 5. The change of emulsion structure due to change of membrane pore size (water volumetric concentration ≈17% and emulsion of 0.5% of span'80 and tween'60). Two mixtures have been used and structure measured after one month of their preparation; the width of shots ≈130 μm.

prepared with the help of membranes of different pore size. It was found that the change of membrane pore size leads to receiving emulsions of different structure and leads to a remarkable change in the emulsion viscosity (Fig. 4). The reduction of pore size leads to preparation of emulsion with finer water droplets and larger number density (Fig. 5), and so the interaction between water droplets is increased producing flow higher internal friction or higher viscosity. This result is comparable with those of other investigations [35,36]; the lower the droplet size of dispersed phase, the larger the emulsion viscosity and the better the emulsion homogeneity (Fig. 5). The emulsion of large droplet size possesses viscosity lower than that for emulsion of low size (because the droplet size departs away from the molecular size and so the internal flow friction is slightly changed). The last group of emulsions was used to determine the effect of emulsion structure on diesel engine performance; as the second step of this work.

In the final stage of the work, the diesel engine performances working on traditional diesel fuel (designated as DF) and WFE with different structures (using membrane of pore size 0.2 μm and 0.45 μm; designated as WFE-0.2 and WFE-0.45, respectively) have been studied (Figs. 6 and 7) and the following results are obtained:

- Use of WFE compared with diesel fuel reduces the concentration of NO_x, and C_nH_m in the exhaust gases and reduces the exhaust gas smoke level (N).
- The best effect of using WFE on the reduction of engine emissions occurs at engine load more than 75% of total load.
- The use of emulsion with smaller water droplet size provides greater reduction of C_nH_m (more than 35%) and smoke level N (more than 80%) in addition to the increase of engine effective brake efficiency η_e (up to 20%).
- The emulsion with larger water droplet size provides greater reduction of NO_x emissions.
- The effective engine efficiency is always improved at the entire range of working loads when WFE have smaller water droplet size (WFE-0.2) up to 1.2 times the engine efficiency when DF is used, and only improved at the medium and high engine loads when WFE of larger water droplet size is used (WFE-0.45).

The notable results of the emulsified fuel having smaller water droplet size is related to the positive influence of homogeneity of size distribution and the increase of the surface contact between fuel and water droplets on different processes within diesel engine cylinder in particular fuel spray, mixture formation, and combustion. This influence leads to the reduction of all engine emissions. However, the combustion improvement when WFE of smaller droplets is used leads to higher concentration of NO_x compared with that of emulsion having larger droplet size. The emulsion having large size of water droplets has a negligible effect on the smoke level at high engine speed and slight effect at low speed. This effect may be owing to the necessity of time to complete the water phase change to vapor as well as for possibility of micro-explosion occurrence. At high engine speed the possibility for micro-explosion

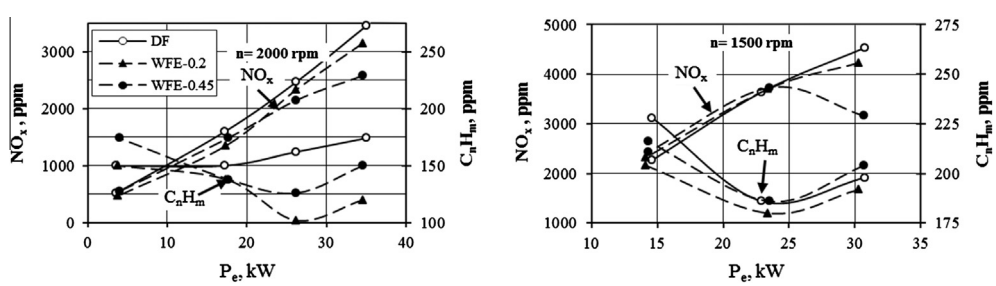

Fig. 6. The change of emission concentration (nitrogen oxides and unburned hydrocarbons) with engine load at engine speed (n) of 1500 and 2000 rpm using diesel fuel (DF) and WFE with different structure (WFE-0.2 and WFE-0.45) after month of their preparation.

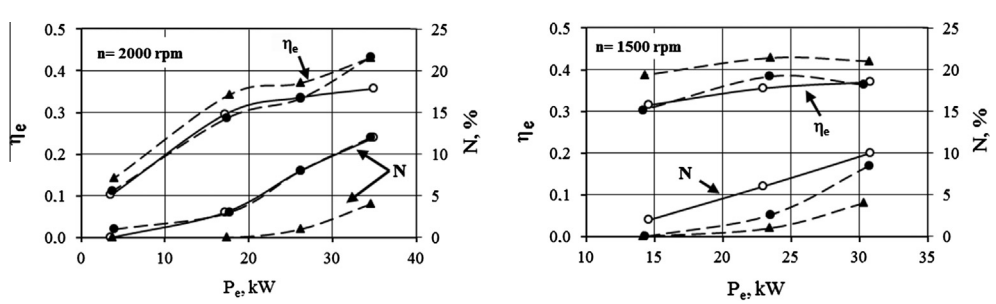

Fig. 7. The change of exhaust gas smoke level (N) and the engine effective brake mechanical efficiency (η_e) with engine load at engine speed (n) of 1500 and 2000 rpm using diesel fuel (DF) and WFE with different structure (WFE-0.2 and WFE-0.45) after month of their preparation.

may be attained during the expansion stroke. The remainder time until gas exhausts may be low enough to oxidize the formed soot during fuel cracking via active radicals formed from water dissociation. Thus the emitted amount of soot may be not changed or may be increased due to the temperature decrease in the result of water evaporation and low heat content. But the increase of contact area between water and fuel for emulsion of smaller water droplet size enhances the heat and mass transfer between fuel and water, and so the mixing process is improved in addition to better distribution of generated active radicals leading to notable reduction of smoke level.

4. Conclusion

1. The built emulsion preparation unit and the proposed method to regulate the emulsion structure stabilized by mixing emulsifiers have been confirmed to produce identical emulsions with different structures.
2. It is not only the increase of water content within WFE emulsion but also the reduction of water droplet size result in an increase of the emulsion viscosity.
3. The use of WFE results in increasing the engine efficiency up to 1.2 times the engine efficiency operated with pure diesel fuel.
4. The use of WFE has a notable environmental impact on the reduction of engine emissions (nitrogen oxides and unburned hydrocarbons) and on the reduction of exhaust gas smoke level.
5. The emulsion structure has a clear effect on the engine performances; the great impact of WFE having large water droplet size occurs on the emissions of nitrogen oxides, while that of smaller water droplet on emissions of unburned hydrocarbons and the smoke level of exhaust gases.

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