AN OVERVIEW ON COMBUSTION AND PERFORMANCE CHARACTERISTICS OF DIESEL ENGINE USING DIESEL-WATER EMULSION

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Rezumat. Lucrarea prezintă un review asupra realizărilor experimentale privind efectele emulsiei diesel-apă asupra caracteristicilor de ardere şi a parametrilor de performanţă ai motoarelor diesel; de asemenea, sunt evidenţiate particularităţile, avantajele şi dezavantejele utilizării combustibilului diesel emulsionat cu apă. Aspectele principale care sunt discutate detaliat includ: întârzierea la aprindere, micro-explozia, variaţia presiunii, degajarea de căldură, puterea motorului, randamentul termic şi consumul de combustibil. Utilizarea emulsiei combustibil diesel-apă ca şi combustibil pentru motoarele diesel este o metodă efectivă de reducere a emisiilor.
Cuvinte cheie: emulsie combustibil diesel-apă, întârzierea la aprindere, micro-explozia, consumul de combustibil, emisii.

Abstract. This paper presents a review on experimental achievements regarding the effects of diesel-water emulsions on burning characteristics and performance parameters of diesel engines; it also highlights peculiarities, advantages and disadvantages of the utilization of water emulsified diesel fuel. The main aspects which are discussed in detail include: ignition delay, micro-explosion, pressure variation, heat release, engine power, thermal efficiency and fuel consumption. Using diesel-water emulsion as fuel for diesel engines is an effective technique in reducing emissions.
Keywords: diesel-water emulsion, ignition delay, micro-explosion, fuel consumption, emissions.

1. INTRODUCTION

Diesel engine is the most combustion-efficient engine because it gives better fuel to power conversion yield. Modern diesel engines are complex systems that burn a carefully controlled mixture of fresh air, burnt gases, and fuel in order to produce the desired mechanical work at the lowest possible fuel consumption and pollutant emissions [1].

Vehicles powered by a diesel engine are considered one of the primary sources of air pollution, especially in metropolitan areas, nevertheless it is expected that diesel engines will continue to be widely used in the foreseeable future. The functioning of diesel engines produces emissions that contribute to the enhancement of the greenhouse effect, produce acid rains, deteriorates the ozone layer in the stratosphere, and affect the human respiratory health [2].

It has been demonstrated that satisfactory performance of a diesel engine is affected by the heterogeneous nature of combustion processes, which can also result in injurious outcomes such as severe knocking and high emission levels of oxides of nitrogen (NO_x) and solid particles.

Considering all these facts, the utilization of emulsified diesel fuel as an alternative fuel in internal combustion engines has been proved to be a feasible technique for reducing considerably the various injurious effects and improving fuel efficiency [3-5].

Volatile fossil fuel prices in recent years and strict engine out emission regulations has stimulated significant research thrust in diesel-water emulsion.

Water-oil emulsion is a homogeneous mixture between water with the base diesel fuel on volume basis, and by the addition of an appropriate surfactant will increase its stability. This is a convenient renewable fuel option since the engine does not require any prior or post modification. Emulsified diesel fuel present more advantages, such as: a better mixing of fuel and air due to an additional momentum in jet behavior and the micro-explosion phenomena that enhance further fuel atomization [6].

Most experimental investigation of engine performance and exhaust gas emission were made at full load conditions. In one of these studies was evaluated the effect of 13% by volume diesel-water emulsion on public buses in Athens and it has been reported higher fuel consumption, improvement in smoke and slight reduction in NO_x emission [7].

Experimental study of two-phase (water-in-oil) and three-phase (oil-in-water-in-oil) emulsion fuels has also revealed lower NO, soot and black smoke opacity while experiencing higher BSFC, HC and CO emission [8,9]. Similar results for water with diesel emulsion fuel are also submitted in recent experimental studies [10,11].

In another recent study, the authors conducted experiments with up to 30% water emulsion and reported comparable torque, power and thermal efficiency for 5% and 10% emulsion [12]. They also observed an increase in BSFC, and reduction in exhaust temperature and NO_x with increasing water percentage.

This paper presents a review on experimental achievements regarding the effects of diesel-water emulsions on burning characteristics and performance parameters of diesel engines; it also highlights peculiarities, advantages and disadvantages of the utilization of water emulsified diesel fuel.

2. COMBUSTION CHARACTERISTICS

Ignition delay of fuels and the flame lift-off are important properties of combustion sprays, which determine a range of diesel engine operating characteristics such as combustion efficiency, noise, soot emission, and ease of starting. The ignition occurs when a significant fraction of chemical energy of fuel is released, indicating the start of combustion. The chemical release is a result of a series of physical processes, such as the atomization of the fuel jet, the vaporization of the fuel droplets, air entrainment into the fuel jet, and its mixture with fuel vapor and chemical processes, such as pre-combustion reactions of fuel, air, and residual gases [13].

In general, the size of the fuel droplet and its volatility should significantly affect the ignition delay. Thus, the ignition delay of a single fuel droplet can be expressed by the evaporation and chemical reaction time [14].

K.A. Subramanian [15] presented a comparison in the effects of water–diesel emulsion and water injection into the intake manifold on performance, combustion and emission characteristics of a DI diesel engine under similar operating conditions. The water to diesel ratio was 0.4:1 by mass for both methods in order to assess same potential benefits. All tests were done at the constant speed of 1500 rpm at different outputs. The static injection timing of 23°BTDC was kept as constant

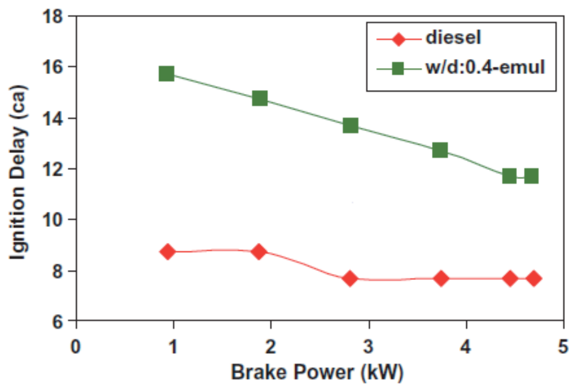

Fig. 1. *Comparison of ignition delay between emulsion and diesel fuel [adapted from 15]*

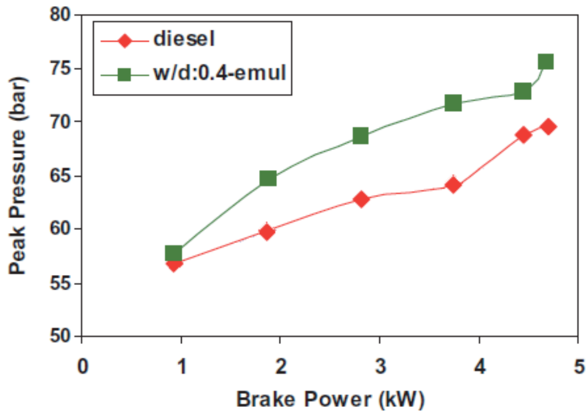

Fig. 2. *Comparison of peak pressure between emulsion and diesel fuel [adapted from 15]*

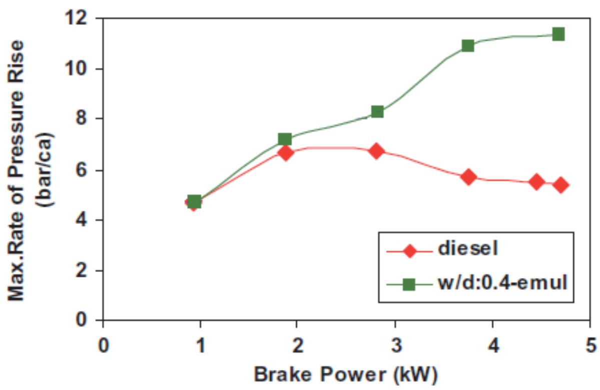

Fig. 3. *Comparison of ignition delay between emulsion and diesel fuel [adapted from 15]*

for all experimental tests. The emulsion was prepared using the surfactant of HLB: 7. His experimental results showed that the ignition delay is increased when using emulsion (Fig. 1), leading to a prolonged premixed combustion phase and the presence of water in contact with diesel will increase the specific heat of the droplets (since the specific heat of water is higher than that of diesel). The peak pressure and maximum rate of pressure rise result also in higher values with the emulsion due to the high ignition delay (Figs. 2 and 3).

Cook et al. [14] reported that low to moderate levels of water emulsification reduces particulate matter (PM) emission, particularly under rich operations. Therefore, the maximum fuel-air ratio for engine operations that restricts the smoke formation is also extended, but excessive water addition tends to overreach this beneficial effect. An optimum level of water content is considered to be from 10 to 20 percent by volume. Moreover, as long as equal amounts of fuel are supplied, water addition has only a very small effect on the indicated mean effective pressure (IMEP). Finally, the emission of PM and the IMEP are not influenced by the addition of small quantities of surfactant and the precise injection timing.

Wang et al. [16] have showed that while water emulsification can prolong the ignition delay, the influence is minimal for fuels which are sufficiently volatile. These volatile fuels, however, are prone to extinction. On the other hand, for fuels which are less volatile than water, micro-explosion is possible, through either violent terminal explosion or continuous mass ejection. However, the net effect in shortening the droplet lifetime is significant only if the fuel is sufficiently non-volatile. The onset and intensity of micro-explosion for such fuels are further enhanced with increasing water content, at least up to the maximum amount of 30% experimented. As a final conclusion, they suggested that a fuel blending strategy could be an optimum water-oil composition that consist of sufficient amount of volatile fuels to facilitate ignition, sufficient amount of less-volatile fuels to promote micro-explosion, and with a variable amount of water addition in order to control the actual droplet lifetime as well as other engine performance parameters such as power and the proportion of soot and NOx emissions. Such a blending strategy merits further study at both the fundamental and practical levels.

Yuan – Chung Lin et al. [17] reported results of test performed in a four cylinders, four stroke, direct injection, water-cooled diesel engine, which used the premium diesel fuel (PDF) as the reference fuel, then combined with a emulsion with an additive of bio-solution NOE-7F (Yung Li Co. Ltd., Taiwan), made from natural organics in 10 % by volume and soy-biodiesel of 10, 20, and 30% ratios by volume. Their results indicated that, with the exception of water 10% and biodiesel 30%, the emulsified fuel did increase the energy efficiency, due to a raise of the emulsified diesel temperature up to 105°C, which evaporated rapidly, brooked the fuel into smaller droplets, and hence this led to a better air/fuel mixing. Thereby it occurred a second atomization of water-in-diesel in the cylinder, that created an easier mingle of water particles with the fuel. These hot particulates reacted with water and produced flammable gas, CO and H_2. Even when water partially consumed the latent heat, the loss of latent heat was still less than the heat released from the combustion of flammable gas. This result in the increase of energy efficiency for the test emulsified fuel.

Jeong et al. [18] investigated experimentally the characteristics of auto-ignition and micro-explosion behaviors of one-dimensional arrays of fuel droplets suspended in a chamber with high surrounding temperature, at various droplet spacing, number of droplets and surrounding temperatures. The fuels used were pure n-decane and emulsified n-decane with varied water contents ranging from 10 to 30%. They reported the following results: The ignition delay appears to be increased as the space between droplets enlarges for a water amount as high as 30%, but as the droplet spacing is narrowed and the number of droplets grows, the ignition delay time is decreased. Full combustion time extends significantly, because of the increased ignition delay (Fig. 4). The time at which a micro-explosion initially occurs is generally unchanged, regardless of the number of droplets or the droplet spacing. Nevertheless, the micro-explosion tends to become

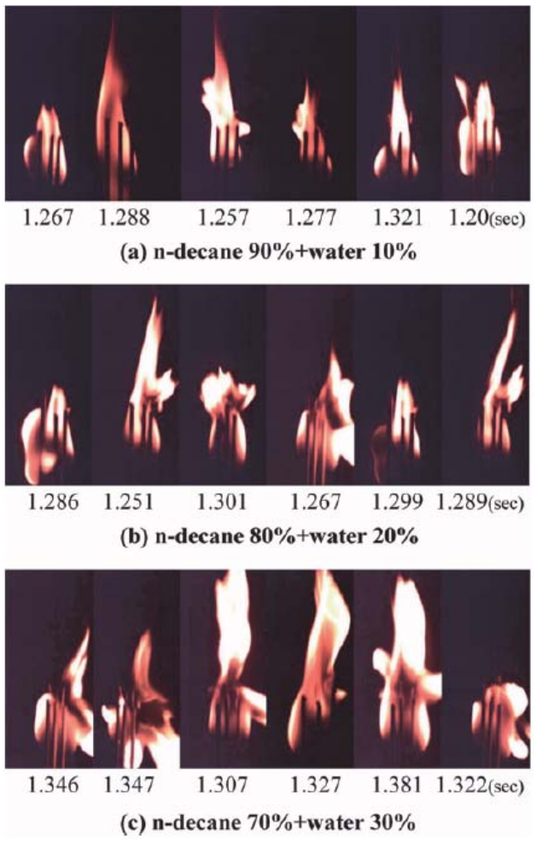

Fig. 4. *Several cases of micro-explosion of emulsified n-decane droplet array at the starting time of micro-explosion (T_a=920 K, D=1.0 mm, Droplet n=3) [18]*

stronger as the water percentage increase and the starting time of the micro-explosion tends to become earlier as the number of the droplet grows.

At medium and high engine loads, the combustion of the micro-emulsion start before the top dead center (BTDC), so the increase in ignition delay results in a strong premixed burning phase leading to a raised pressure in the cylinder. There is no evident variation of the peak pressure rise rate with the quantity of water in the micro-emulsion. Furthermore, the micro-explosion of water droplets can improve the spray atomization, which results in a faster combustion [19].

Ghojel et al. [20] presented an experimental investigation on the effect of high injection pressure and water content on the ignition delay and lift-off length of combusting DWE sprays in a constant volume chamber Injection pressures up to 100MPa were used to inject the fuels into the combustion chamber at different ambient temperatures. A reference fuel and three emulsified fuels with different water contents were used. The chamber pressure curves obtained using a piezoelectric pressure sensor and flame images recorded using a high speed digital camera were analyzed to study ignition delay and spray lift-off of the fuels. The results showed the following: The ignition delay of the emulsified fuel is always higher than that of the standard diesel fuel. The injection pressure has little effect on ignition delay of DWE, whereas the ambient temperature has significant effect, particularly at high water content. For engine operation requiring shorter ignition delays when DWE with higher water content are used, there may be a need for modifications to the injection timing and injection pressure profiles in order to increase the temperature of the charge at the moment of fuel injection. Injection pressure and fuel water content cause the flame lift-off to increase, allowing more air to be entrained before the combustion, leading to leaner mixtures within the fuel jet during the quasi-steady combustion. As a consequence, in-cylinder soot formation could be reduced. Ambient temperature has the opposite effect on the flame lift-off, which is probably caused by the stronger rates of fuel vaporization and combustion under high temperatures. This implies that there may be a need for a trade-off between ignition delay and lift-off in actual engines operating on DWEs.

3. PERFORMANCE CHARACTERISTICS

Fahd et al. [21] investigated the effect of 10% water emulsion diesel on engine performance and emissions as against base diesel fuel. The experiments were performed in a four cylinder 2.5 L DI turbocharged Toyota diesel engine at four different engine loading conditions (25%, 50%, 75% and 100% load). During experiments, the engine speed was varied from 800 rpm to 3600 rpm in steps of 400 rpm for each load condition. From this experiment it was observed that both fuels exhibit nearly same in cylinder pressure traces and heat release rates at different engine load and speed conditions. The diesel emulsion produces less output power and engine efficiency as compared to neat diesel fuel. Nevertheless, it was noted that DWE10% produces better engine efficiency as compared to diesel fuel at higher engine load. Besides these, DWE10% shows higher brake specific fuel consumption (BSFC) for all engine operating conditions.

3.1. Engine power

In most experimental works [20-25] it has been observed that with the addition of water in the emulsified fuel the engine power decreases at all load conditions, which can be attributed to the lower heating value of diesel-water emulsion (Fig. 5).

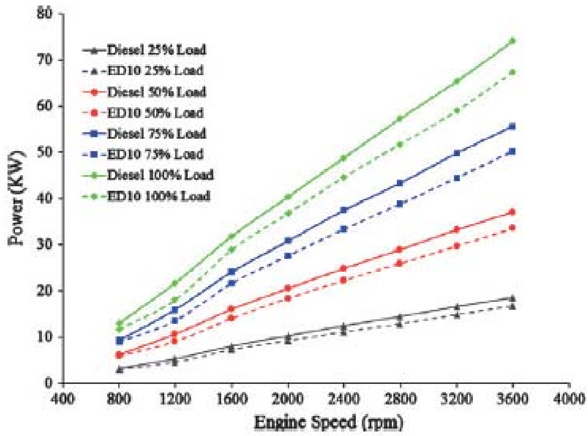

Fig. 5. *Engine power output for diesel and DWE10 fuels at varying engine speed and load conditions [21]*

3.2. Thermal efficiency

In some scientific papers [12, 21] it was indicated that diesel emulsion with water demonstrates lower thermal efficiency than diesel fuel for all conditions and the difference of thermal efficiency between these two fuels decreases as the engine load increases (Fig. 6). Lower thermal efficiency is due to the lower heating value of emulsified fuel leading to decrease fuel energy to mechanical power conversion. At lower load, engine needs to produce power overcoming the frictional losses and the heat sink phenomena of water particles, but as the engine load is increased,

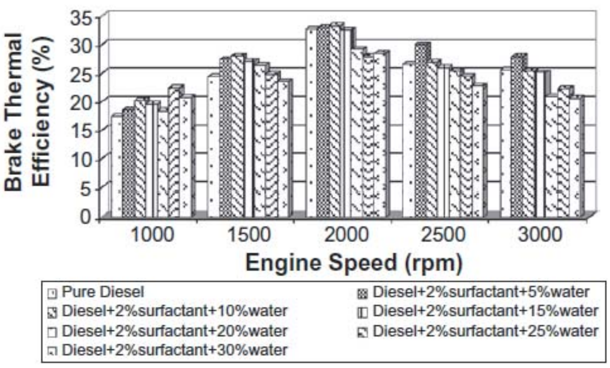

Fig. 6. *Comparison of brake thermal efficiency between DWE and pure diesel [12]*

more power can be produced against frictional losses, leading to improved efficiency.

3.3. Fuel consumption

The results of certain experimental studies indicated that the BSFC decreases with the increase in engine load [21-25]. This is due to the fact that the total energy release increases with the increase of engine load; practically the friction loss is almost the same, so the proportion of output power increases. It was also reported that at higher speed if the percentage of water in the emulsion increases, the BSFC increases. And most importantly, BSFC for diesel emulsion with water is higher than pure diesel fuel due to its lower calorific value which increases fuel consumption for same desired power output (Fig. 7).

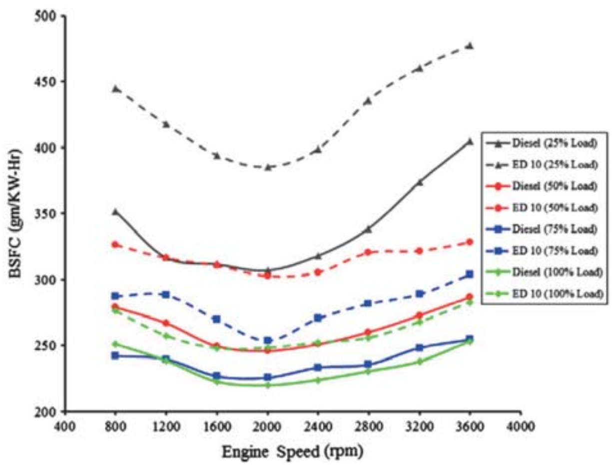

Fig. 7. *BSFC for diesel and DWE10 fuels at varying engine speed and load conditions [21]*

4. CONCLUSIONS

In general, diesel-water emulsion was proved to be a very effective technique in improving full load brake thermal efficiency and lowering NOx and smoke levels.

Diesel-water emulsion results in higher ignition delays, peak pressures and rates of pressure rise. Full combustion time extends significantly, because of the increased ignition delay. The time at which a micro-explosion initially occurs is generally unchanged and the micro-explosion tends to become stronger as the water percentage increases. Furthermore, the micro-explosion of water droplets can improve the spray atomization, which results in a faster combustion and suppress the formation of soot and unburned hydrocarbons.

It has been demonstrated that while diesel-water emulsification can prolong the ignition delay, the influence is minimal for sufficiently volatile fuels, but these fuels are prone to extinction. Contrariwise, for fuels which are less volatile than water, micro-explosion is possible, and the net effect in shortening the droplet lifetime is significant only if the fuel is sufficiently non-volatile. The onset and intensity of micro-explosion for such fuels are further enhanced with increasing water content, at least up to the maximum amount of 30% experimented.

Considering all this, a fuel blending strategy may be suggested in that an optimum water-oil composition should consist of sufficient amount of volatile fuels to facilitate ignition, sufficient amount of less-volatile fuels to promote micro-explosion, and with the amount of water addition being variable to control the droplet lifetime as well as other engine performance parameters such as power and the formation of soot and NOx emissions.

Most experimental results have indicated that the brake specific fuel consumption (BSFC) decreases with the increase in engine load, due to the fact that the total energy release increases with the increase of engine load; practically the friction loss is almost the same, so the proportion of output power increases. It was also reported that at higher speed if the percentage of water in the emulsion increases, the BSFC increases. And most importantly, BSFC for diesel emulsion with water is higher than pure diesel fuel because of its lower calorific value which increases fuel consumption for same desired power output.

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