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WATER-IN-DIESEL EMULSIONS AS AN ALTERNATIVE FUEL FOR DIESEL ENGINES. PART II: PERFORMANCE OF DIESEL ENGINES FUELED WITH WATER-IN-DIESEL EMULSIONS. A LITERATURE REVIEW

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ABSTRACT

This paper presents the recent advances of water-in-diesel emulsion fuel studies, especially the impact of using this emulsion fuel to the performance and emissions of diesel engine. Studies revealed that the onset and the strength of micro-explosion process give strong effect with regard to the combustion efficiency inside the combustion chamber.

Most of the researchers tested emulsions with water content of 5-40% in diesel fuel. Some studies concluded that 20% water in the emulsion fuel gives the optimum engine performance. Many researchers and experts agree that the reason why there is a slight drop in brake power and torque is the fact that water-in-diesel emulsion fuel has a lower heating value than a neat diesel fuel, thus less energy is released during combustion.

In general, the results suggest that the water emulsification has a potential to slightly improve the brake efficiency and to significantly reduce the formation of NO_x*, soot, hydrocarbons and PM in the diesel engine.*

Some factors may affect the experimental results that need to be considered, such as the effect of volatility of the base fuel, the water content of the emulsion, emulsion stability, ambient temperature, pressure, type of surfactant and engine test conditions: engine load, speed, injection timing and compression ratio.

KEYWORDS: water-in-diesel emulsion, performance, emissions, diesel engine, combustion

1. Introduction

Diesel engines have been used in heavy duty applications for a long time [1] and, nowadays, more and more attention is paid to diesel engines in transportation, industrial and agricultural applications due to their high efficiency and reliability [2].

A good fuel for diesel engine should bear characteristic features such as short ignition lag, sufficiently high cetane rating in order to avoid knocking, suitably volatile in the operating range temperatures for good mixing and combustion, easy startup characteristics, limited smoke and odor, suitable viscosity for the fueling system, free from corrosion and wear, and ease of handling [3].

Higher fuel efficiency in the diesel engine is achieved due to the high compression ratios along with relatively high oxygen concentration in the combustion chamber [4].

The introduction of water prolongs the ignition delay, increases the amount of fuel burned and the rate of heat released in the kinetic burning period. In the diffusive burning period, the temperature is generally lower in the cylinder when water is added. The change in the maximum cylinder pressure is insignificant [5].

Primary pollutants emitted from diesel engines are particulate matters (PM), black smoke, nitrogen oxides (NO_x), sulphur oxides (SO_x), unburned hydrocarbon (HC), carbonmonoxide (CO), and carbon dioxide (CO_2) [6].

Water-in-diesel emulsions are fuels for regular diesel engines. The advantages of an emulsion fuel are the reductions in the emissions of nitrogen oxides and particulate matters, which are both health hazardous, and the reduction in fuel consumption due to better burning efficiency. An important aspect is that diesel emulsions can be used without engine modifications [7].

Most emulsions are not thermodynamically stable, but as a practical matter, quite stable emulsions can occur that resist demulsification treatments and may be stable for weeks / months / years. Most meta-stable emulsions that will be encountered in practice contain oil, water and an emulsifying agent (or stabilizer) which is usually a surfactant, a macro-molecule, or finely divided solids [8].

This review presents the influence of water-in-diesel emulsion on the diesel engine performance and the effects of water-in-diesel emulsion fuel on combustion process and emissions.

2. Combustion process

The combustion process is generally characterized by factors such as injection characteristics, spray penetration, evaporation, chemical and physical atomization and mixture ignition, engine cylinder pressure and temperature, and heat release characteristics. Figure 2 presents the primary and secondary atomization in spray flame of an emulsified fuel [6].

The interest in water-in-diesel emulsions derives from the fact that water in the form of micrometer-sized droplets exerts some positive effects on the combustion of fuels. When an emulsion fuel is heated, the water droplets are vaporized first because water is more volatile than diesel under superheat conditions. The vaporization of water will cause the „explosion" of the continuous hydrocarbon phase.

This phenomenon, known as micro-explosion, helps in the atomization of fuel, accelerating fuel evaporation rate and enhancing fuel-air mixing process, thereby improving the process [1].

Micro-explosion is an important phenomenon in the secondary atomization process of water-in-diesel emulsion fuels. Generally, this phenomenon is affected by volatility of base fuel, type of emulsion, water content, diameter of the dispersed liquid, location of the dispersed liquid and ambient conditions like pressure and temperature [6].

Sheng, Zhang and Wu [9] observed that the water dots of 0.001 mm in emulsion droplets can be recognized and a no-water layer is found near the surface of the droplet (Figure 1). The micro-explosion can hardly be observed below 733 K. At 823 K, the explosion takes place early and is slightly weaker. In lower gas pressure cases, the velocity of torn fragments of droplets after explosion is much higher than that in higher gas pressure, due to lower gas density.

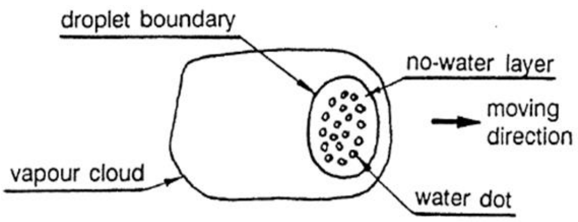

***Fig. 1.** Micro-structure of the vaporing emulsion droplet* [9]

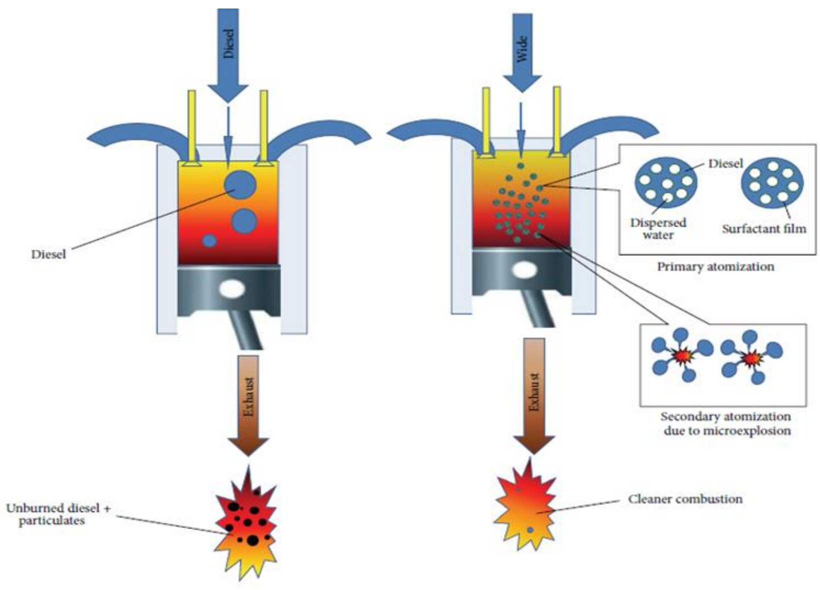

***Fig. 2.** Primary and secondary atomization in spray flame of emulsified fuel* [6]

The study of the combustion process was difficult to perform since there has not been any optical access to the combustion chamber. As a result, more focus was given to the cylinder and thermocouple readings for the engine wall and inlet and exhaust temperatures to study the performance of combustion [6].

The temperature in the combustion chamber is the key factor for the utilization of emulsion. Micro-emulsion will take place in a certain temperature range and becomes stronger at a proper temperature. Higher pressure in the combustion chamber has little effect on the occurrence of the explosion, but the penetration of fragments of torn droplets will be much lower due to the denser gas in the combustion chamber. This gas may weaken the effect of micro-explosion on the improvement of air-fuel mixing. The explosion will take place more easily for larger initial droplet diameters. The energy of explosion is strong enough to emit fragments of torn droplets to a distance several millimeters away from the spray boundary, if the gas temperature is suitable [9].

3. Performance of diesel engine fueled with water-in-diesel emulsions

Fahd *et al.* [10] investigated the effect of 10% water emulsion diesel (ED10) on the engine performance and emission characteristics and the results were compared to the base diesel fuel (Euro 4). 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) in order to analyze the effect of emulsion diesel over the entire engine load condition. For each load, the engine speed was varied from 800 rpm to 3600 rpm in steps of 400 rpm. The water-in-diesel emulsion (ED10) produces less output power and engine efficiency as compared to neat diesel fuel (Figure 3). Besides these, W/D E10% shows higher brake specific fuel consumption (BSFC) for all engine operating conditions (Figure 4).

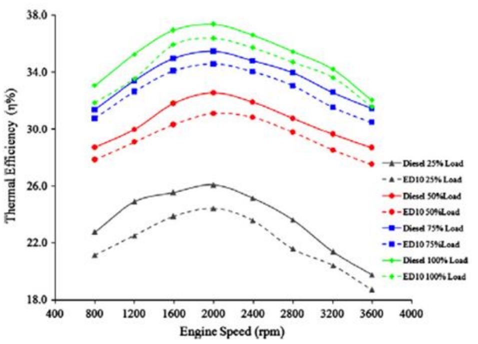

Fig. 3. *Thermal efficiencies for diesel and ED10 fuel vs engine speed and load* [10]

Reduction in exhaust gas temperature is observed for ED10 fuel and at higher engine load conditions. In addition, ED10 demonstrates lower NO emission at all load conditions and higher CO emission at low load and low speed condition which eventually gets significantly reduced at higher engine speed.

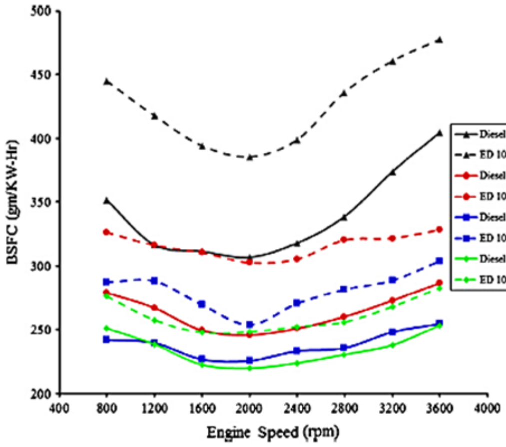

Fig. 4. *Brake specific fuel consumption for diesel and ED10 fuels vs engine speed and load* [10]

Armas *et al.* [11] investigated the effect of water–oil emulsions on the engine performance and on the main pollutant emissions, NO_x, total hydrocarbons (THC), soot, particulate matter (PM) and its composition. Renault F8Q turbocharged intercooler IDI Diesel engine was tested under five different steady state operating conditions, selected from the transient cycle for light duty vehicles established in the European Emission Directive 70/220. Tests were performed using a commercial fuel as a reference and an emulsified fuel (water-in-diesel emulsion with 10% water percentage and with the surfactants recommended by Repsol-YPF company – polyethylene glycolemonoleate and sorbitol-esesquioleate) for each operating condition.

The results reported here suggest that the water emulsification has the potential to slightly improve the fuel consumption, the brake efficiency and to significantly reduce the formation of thermal NO, soot, hydrocarbons and PM in the diesel engine [11].

Suresh et al. [12] investigated the emissions and performance characteristics of a four-stroke diesel engine operating on water in diesel emulsified fuels and its CFD (Computational Fluid Dynamics) analysis of NO_x emission. Emulsion fuels with varying contents of water in diesel (5%, 10%, 15% and 20%) are prepared and stabilized by sorbitan-monooleate surfactant. The experimental results reveal that 20% water-in-diesel reduces 45% of NO_x emission. Figure 5 presents the brake power versus

NO_x and it is observed that water-in-diesel fuel with 20% water registers the lowest values of NO_x.

The exhaust gas temperature and smoke emissions are drastically reduced for the emulsion fuels compared to the pure diesel. When water is added to diesel fuel, brake thermal efficiency is slightly reduced. It is acceptable if we are to consider the NO_x emissions characteristics.

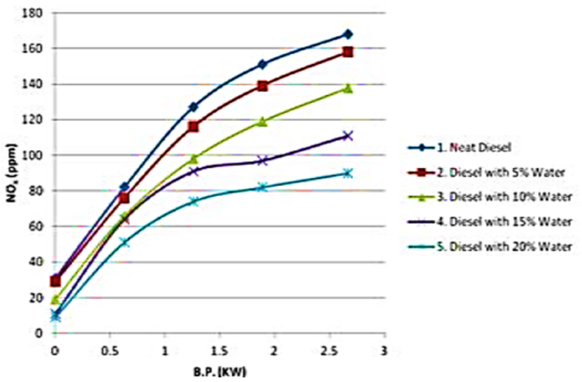

***Fig. 5.** NO_x emission vs brake power* [12]

According to a report by Sadler [13], an application of 13% water content (not mentioned whether by volume or mass percentage) in the emulsified fuel in UK has brought 13% and 25% reduction of NO_x and PM, respectively.

Ahmad et al. [14] investigated the effect of water-in-diesel emulsion fuel (W/D) originating from low-grade diesel fuel (D2) on the combustion performance and emission characteristics of a direct injection diesel engine under varying engine loads (25–100%) and constant engine speed (3000 rpm). Four types of W/D are tested, which consist of different water percentages (5%, 10%, 15% and 20%), with a constant concentration of 2% of surfactant and labeled as E5, E10, E15 and E20, respectively. It is observed that NO_x (Figure 6) and PM (Figure 7) are found to be reduced for all types of W/D.

The carbon monoxide (CO) and carbon dioxide (CO_2) emissions increase compared to D2 at low load and high load, respectively. E20 is reported to be the best in reducing NO_x and PM with an average reduction of 41% and 35%, respectively, in every load condition.

Attia and Kulchitskiy [15] studied the effect of the structure of water-in-diesel fuel emulsion (WFE) on a three-cylinder diesel engine performance. Based on membrane emulsification, two different membranes of pore sizes of 0.2 μm and 0.45 μm have 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 of 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%.

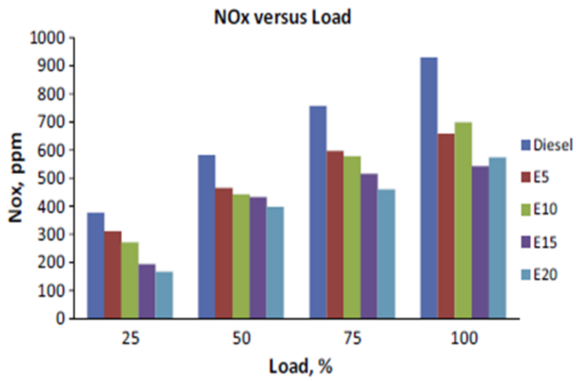

***Fig. 6.** Formation of PM for D2 and W/D (E5, E10, E15 and E 20) under varied loads (25%, 50%, 75% and 100%)* [14]

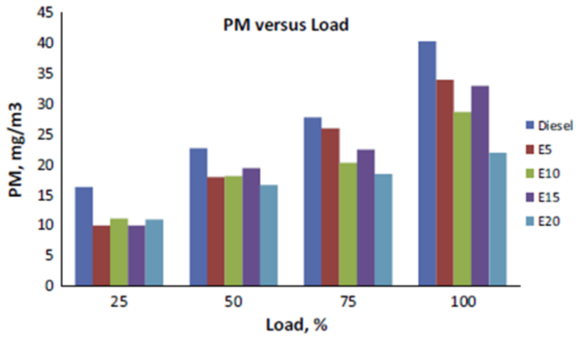

***Fig. 7.** Formation of NO_x for D2 and W/D (E5, E10, E15 and E 20) under varied loads (25%, 50%, 75% and 100%)* [14]

Alahmer [16] investigated the effect of emulsified diesel fuel on the engine performance and on the main pollutant emissions for a water-cooled, four-stroke, four cylinders, and direct injection diesel engine. Emulsified diesel fuels with water content in the of range 0-30% by volume were used. The experiments were conducted in the speed range from 1000 to 3000 rpm. While the brake specific fuel consumption (BSFC) has a minimum value at 5% water content and 2000 rpm, the torque, the break mean effective pressure and thermal efficiency (Figure 8) are found to have maximum values under these conditions. The emission of CO_2 was found to increase with engine speed and to decrease with water content. NO_x produced from emulsified fuel is significantly less than NOx produced from pure diesel under the same conditions (Figure 9), and as the percentage of water content in the emulsion increases, the emitted amount of oxygen also increases.

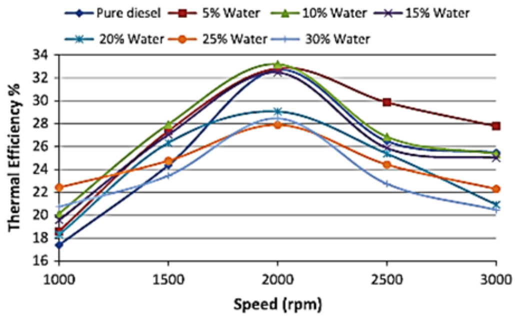

Fig.8. *Thermal efficiencies for pure diesel, 5%, 10%, 15%, 20%, 25% and 30% water addition* [16]

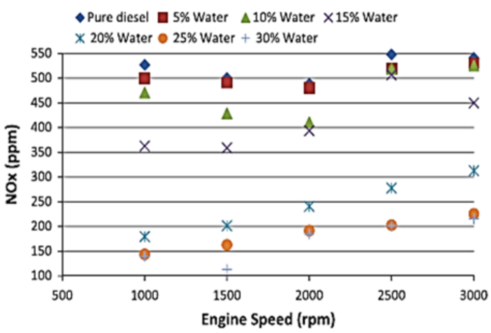

Fig. 9. *NO_x emission for pure diesel, 5%, 10%, 15%, 20%, 25% and 30% water addition* [16]

It was found that, in general, the use of emulsified fuel improves the engine performance and reduces emissions [16].

Canfield [17] examined the effects of combusting a mixture of diesel fuel, water, and surfactant on the nitrogen oxides (NO_x) emissions from a compression ignition diesel engine. The data shows significant NO_x emission reduction with up to 45% water, by volume, in the fuel. These results are correlated with the first thermodynamic law and equilibrium combustion products analyses to estimate the adiabatic flame temperature of the standard fuel and fuel-water emulsion cases. Results indicate that thermal NO_x is indeed reduced by quenching and flame temperature suppression, confirming the reports in the literature. Recommendations are given for further studies, including improving the fuel-water emulsion and considerations for long-term testing.

Ghojel and coworkers [18] reported 29-37% reduction of NO_x emissions when operating on diesel oil emulsion of 13% water content by volume.

Samec *et al.* reported a reduction of 20% and 18% NO_x emission compared to pure diesel fuel with 10% and 15% water content in the emulsion, respectively [19, 20].

Barnes *et al.* [21] investigated the effect of water blended fuel on the performance and emissions of a city bus engine considering 10% water content by volume. They showed a decrease of NO_x with 9% in comparison with the use of neat diesel fuel.

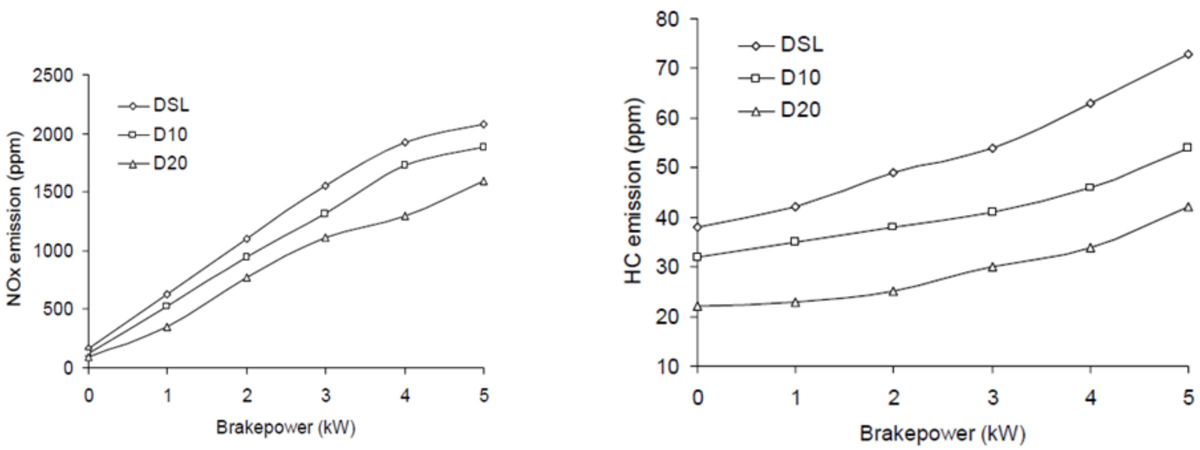

Fig. 10. *NO_x emission (left) and HC emission (right) vs brake power* [22]

Kanaan and Udayakumar [22] studied the effect of water emulsified diesel fuel combustion on brake thermal efficiency, brake specific fuel consumption and NO_x and hydrocarbon emissions in a diesel engine. The experiments were conducted on a single cylinder Kirloskar with direct injection and four-stroke cycle diesel engine at constant speed of 1500 rpm with a fuel injection pressure of 200 bars. The aim of the experimental study was to investigate the effect of diesel (DSL), diesel with 10% water (D10) and diesel with 20% water (D20) on performance and emission in a light duty single cylinder diesel engine.

The water emulsified diesel fuel was prepared by mixing 10% and 20% of distilled water with 90% and 80% of diesel by volume, respectively. Sodium lauryl sulphate was used as surfactant to prepare the emulsion. Sodium lauryl sulphate (0.1%) is added with 100 ml and 200 ml distilled water and mixed with 900 ml and 800 ml diesel to prepare D10 and D20 emulsified diesel fuels, respectively. The mixer was stirred for 2-3 minutes in an electrically operated agitator. As the amount of water in the emulsion increases, the brake thermal efficiency increases. The presence of water in the emulsion increases the expansion work and reduces the compression work resulting in increased net work done during the cycle [22].

The NO_x (Figure 12, left) and hydrocarbon (Figure 12, right) emissions were found to decrease with the increase in water percentage (until 20%) in the emulsified diesel [22].

Nadeem *et al.* [23] studied water-in-diesel emulsion with conventional (sorbitanmonooleate) and gemini surfactants for main pollutant emissions by fuelling it in a four-stroke and four-cylinder engine test bed and concluded that, for 15% water content, there is 71% reduction in PM emission with Gemini surfactant water in diesel emulsion fuel. Emulsified fuels containing 5-15% water contents were prepared using conventional and gemini surfactants and studied in an engine bed XLD 418 (Ford, four strokes, four cylinders, water-cooled, compression ratio: 21.50, total displacement volume: 1753 cc and a maximum output brake horsepower: 60.0 at 4800 rpm) to clarify the changes in the main pollutant emissions (NO_x, CO and PM). The emission of NO_x, CO and PM was reduced using the emulsified fuels instead of neat diesel. The emulsified fuels containing gemini surfactant were the most prominent in the reduction of PM.

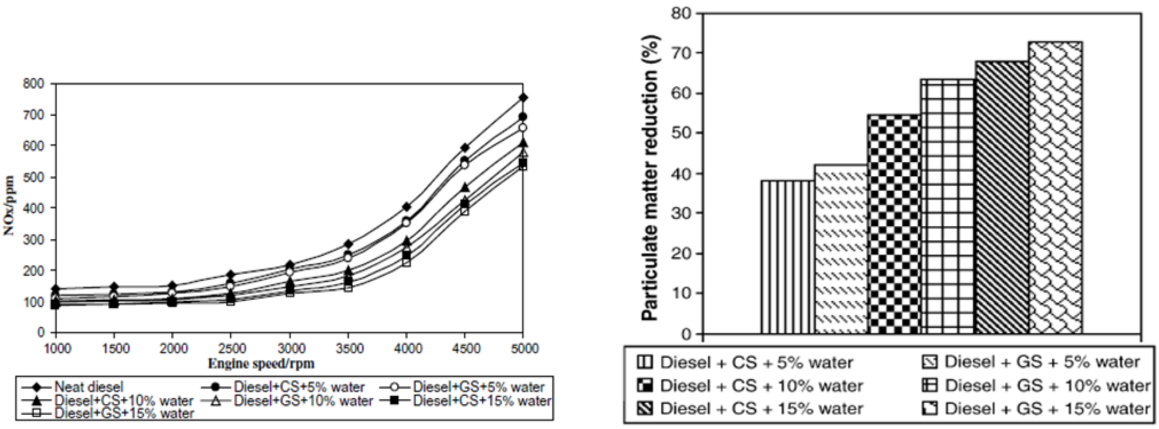

Fig. 11. *NO_x emission (left) and articulate matter emission (right) from neat diesel and emulsified fuels* [23]

In addition, emulsion fuels have higher specific fuel consumption and produce less torque, power and brake mean effective pressure but the difference is insignificant. Water emulsification has a potential to significantly reduce the formation of thermal NO_x (Figure 11, left), CO, SO_x, soot, hydrocarbons and PM (Figure 11, right) in diesel engines [23].

4. Conclusion

Diesel engines have been used in heavy duty applications for a long time and, nowadays, diesel engines are getting more and more attention in transportation, industrial and agricultural applications due to their high efficiency and reliability.

Primary pollutants emitted from diesel engines are particulate matters (PM), black smoke, nitrogen oxides (NO_x), sulphur oxides (SO_x), unburned hydrocarbon (HC), carbon monoxide (CO), and carbon dioxide (CO_2).

The combustion process is generally characterized by factors such as injection characteristics, spray penetration, evaporation, chemical and physical atomization and mixture ignition, engine cylinder pressure and temperature, and heat release characteristics.

Water-in-diesel emulsions are fuels for regular diesel engines.

The research studies were mainly focused on specific engine operation variables and, because of these results, it has become very difficult to draw a general conclusion. The results reported by different researchers are often conflicting, sometimes generating results that are even worse than pure diesel.

Many researchers have concluded that a W/D emulsion fuel with water content of up to 20% can reduce:

- NO_x emissions by up to 45% (in Suresh's experiment), and in most cases up to 20%, compared to standard diesel fuel;
- Emissions of PM, HC and soot with significant percentages compared to standard diesel.

Some characteristics, such as the water percentage, dispersed droplet size and viscosity depending on the engine working conditions, such as engine load and speed, would be an interesting research area that can be explored fundamentally and practically in the near future.

The proven benefit of the water emulsified diesel is that the heat absorption by water vaporization causes a decrease of local adiabatic flame temperature and therefore reduces the chemical reaction in gas phase to produce thermal NO. The fuel with a larger emulsion ratio results in a longer ignition delay and a longer premixed combustion phase. A higher content of water weakens luminous flames and reduces the peak temperature in the diffusion controlled combustion phase and leads to a lower peak pressure and a lower level of NO_x emission.

With the advantage of the energy saving and less environmental pollution for W/D emulsion, together with the newly developed emulsion fuel making device, it will provide a great contribution to the industries, and, at the same time, will reduce the consumption of energy and ensure less pollution to the environment.

Furthermore, it requires a lot of studies and experimental work on the optimization of water content in the emulsion for best engine performance and low emissions so that the best recommendations could be given for the commercialization of water- in-diesel emulsion as an alternative source of energy for future diesel engines.

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