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## Article

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## Research paper

# A comparative study on the performance and emissions from a CI engine fuelled with water emulsified diesel prepared by mechanical homogenization and ultrasonic dispersion method



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## ABSTRACT

In this study, the authors have tried to compare the stability behaviour of water emulsified diesel (WED) prepared by mechanical homogenizer and ultrasonicator. Both types of emulsion have been prepared by adding 10% water and 2% surfactant mixture of Span 80 and Tween 80. The emulsion prepared by ultrasonicator (WED<sub>U</sub>) shows higher stability than that prepared by mechanical homogenizer (WED<sub>M</sub>). Two important physical properties namely, viscosity and density of the prepared WEDs have been measured and compared to those with base diesel. Experimental investigations have also been carried out in a diesel engine using neat diesel as well as WEDs to compare the effect of mechanical homogenization and ultrasonication methods on combustion, performance and emission characteristics of the engine. The emulsion prepared using ultrasonicator shows improved combustion characteristics due to smaller size and more homogeneous distribution of the water particles. Higher brake thermal efficiency and lower brake specific fuel consumption are observed using WED<sub>U</sub>. Both the combustion and the performance behaviours of the engine using emulsions prepared by ultrasonicator show improved characteristics. But, the results are not much encouraging of WED<sub>M</sub>. NO<sub>x</sub> and smoke emissions are noted to be significantly reduced for both types of prepared emulsions. However, the difference in CO emission at full load condition is found to be marginal.

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## 1. Introduction

Since the invention of diesel engines, these are being developed based on performance improvement along with the reduction in pollutant emission. In search of higher performance and lower pollutant emission, researchers are pursuing the use of suitable alternative fuels along with the engine design modification. These alternative fuels include bio-diesel, bio-gas, ethanol and CNG. Attempts have also been taken to use water emulsified diesel (WED) as fuel for compression ignition (CI) engine for the last few decades. The addition of water to the diesel fuel is considered as one of the best effective and economic way to reduce pollutant emission without any modification of the existing diesel engine (Ghojel and Honnery, 2005; Samec et al., 2002; Nadeem et al., 2006). In emission characteristics of a diesel engine, there is a trade-off relationship between NO<sub>x</sub> and PM emission. It has been reported in the literature that both NO<sub>x</sub> and PM emissions are reduced simultaneously when WEDs having different percentages of water are used as fuel in

CI engine (Nadeem et al., 2006; Lin and Chen, 2006b; Sullivan, 1999; Subramanian, 2011; Maiboom and Tauzia, 2011). In water emulsified diesel, water is in dispersed phase and diesel is in continuous phase. The presence of water in fuel changes the physical and chemical kinetics of its combustion and increases heat release rate (Samec et al., 2002).

During the compression stroke after the fuel injection, the heat transfer takes place from high boiling point diesel to low boiling point water (Subramanian, 2011; Lin and Chen, 2008). Due to the difference in the volatility of diesel and water, micro-explosion takes place which results in the formation of many tiny fuel particles (Lin and Chen, 2008; Armas et al., 2005; Iivanov and Nevedov, 1965). This phenomenon is called secondary atomization due to which total surface area of fuel particles increases resulting in better fuel–air mixing. Consequently, improved combustion of the fuel is observed in case of water emulsified diesel. Additional fuel jet momentum due to higher density of WED results in more air aspiration and thus improves the mixing of fuel and air for this fuel (Armas et al., 2005; Pariotis et al., 2006). The secondary atomization reduces the combustion duration and thus more intense combustion occurs around the flame axis (Tarlet et al., 2010). Combustion chamber temperature is significantly reduced

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### Abbreviations

CNG	Compressed Natural Gas
WED	Water Emulsified Diesel
CI	Compression Ignition
NO <sub>x</sub>	Oxides of Nitrogen
PM	Particulate Matter
CO	Carbon Monoxide
BTE	Brake Thermal Efficiency
DI	Direct Injection
cSt	Centistokes
NO	Nitric Oxide
CO <sub>2</sub>	Carbon Dioxide
BSFC	Brake Specific Fuel Consumption
PDI	Polydispersity Index
HLB	Hydrophilic–Lipophilic Balance
WED <sub>M</sub>	Water Emulsified Diesel prepared by Mechanical Homogenizer
WED <sub>U</sub>	Water Emulsified Diesel prepared by Ultrasonicator
DLS	Dynamic Light Scattering
ASTM	American Society for Testing and Materials
TDC	Top Dead Centre
CA	Crank Angle
NO <sub>2</sub>	Nitrogen Dioxide

due to evaporation of water present in the emulsion which is called heat sink effect (Nadeem et al., 2006; Lin and Chen, 2006b). Longer ignition delay due to this heat sink effect results more fuel combustion in premixed mode (Yang et al., 2013; Attia and Kulchitskiy, 2014). Reduced in-cylinder temperature results in less NO<sub>x</sub> formation following Zeldorich mechanism (Alahmer, 2013).

Considering the increase in enormous amount of diesel fuel consumption day by day, a fractional replacement of it by water emulsified diesel means a very new and large application with respect to pollutant reduction and fuel economy. The stability requirements of such emulsions are very obvious and the fuel should be stable for longer time as it is an important issue for smooth and trouble free operation of diesel engine.

Most of the researchers have prepared water emulsified diesel using mechanical homogenizer (Nadeem et al., 2006; Subramanian, 2011; Badran et al., 2011; Fahd et al., 2013; Ashok, 2012; Suresh and Amirthagadeswaran, 2015). Very few works are available in the literature which indicate the application of ultrasonicator in WED preparation as fuel for CI engine (Lin and Chen, 2008). However, Mondal and Mandal (2018, 2017) and Maji et al. (2018) have prepared the water emulsified diesel with the help of ultrasonicator for using as CI engine fuel. If ultrasonic machine is operated at higher frequency, violent and strong physical reaction takes place in the ultrasonic wave transmission medium (Lin and Chen, 2006b). As the ultrasonic wave moves, alternatively negative and positive pressure waves are generated. The cavities are formed in the liquid when the corresponding hydrostatic pressure of the surrounding liquid is less than the pressure generated by ultrasonicator. This process produces much stronger mechanical stirring effect in the liquid mixture than the cutting and shearing effect generated by a mechanical homogenizer. Thus, a much more emulsification is achieved in ultrasonication process to make the emulsion of two immiscible liquids – water and diesel. The positive pressure generated by ultrasonic wave compresses

the cavities resulting heat production from the liquid molecules. When this rate of heat generation is higher than the heat diffusion rate, the surrounding liquids become hot. This phenomenon is called heat spot effect (Lin and Chen, 2006b; Ithnin et al., 2018). The high pressure and the high temperature generated in this ultrasonication process greatly enhance the physical and chemical reaction in the liquid mixture.

Nadeem et al. (2006) produced WED containing 5%–15% water adding conventional Span 80 and Gemini surfactants separately using a mechanical stirrer at 2500 rpm. The surfactant amount in the WED was varied from 0.2% to 1.0%. The emulsion prepared using Gemini surfactant showed better and finer distribution of water droplets compared to those prepared using conventional surfactant. They also reported that 0.5% conventional surfactant and 0.4% Gemini surfactant provided better emulsion stability and hence these quantities were chosen as optimal dosages which were utilized for further experimental works. These emulsified fuels were used in a XLD418 type FORD, 4-stroke, 4-cylinder diesel engine having compression ratio 21.5:1. They reported reduction in power generation and increase in brake specific fuel consumption (BSFC) when emulsified diesel (containing conventional or Gemini surfactants) was used instead of diesel only. But the emissions of pollutants such as NO<sub>x</sub>, CO and PM were found to be reduced using emulsified diesel. However, the emulsified diesel containing Gemini surfactant was more prominent in the reduction of PM. Fahd et al. (2013) used WED containing 10% water and 10% biodegradable surfactant prepared by high speed rotary blending machine in a Toyota 2KD-AD, 4-cylinder diesel engine at different speeds and varying loads. The power generation was found to be lower with WED than that with pure diesel. Brake thermal efficiency (BTE) was also noted to be lower with WED compared to diesel only at low load and comparable at higher loads (75% and 100% load). A 12% increase over neat diesel in BSFC was observed when the engine was operated under full load condition at 3600 rpm. They found reduction in NO<sub>x</sub> emission and increase in CO emission using WED instead of base diesel as fuel.

Ithnin et al. (2018) prepared WED containing 5% water without any surfactant and also with 0.2% Span 80 surfactant and used these fuels to run a single cylinder, DI diesel engine at a constant speed of 3000 rpm. They noted 3.59% and 5.34% increase in BTE for emulsified fuel without and with surfactant, respectively compared to base diesel. On the other hand, the neat brake specific fuel consumptions (considering only diesel part of WED) were 3.89% and 5.55% lower than that using base diesel. They also observed reductions in NO<sub>x</sub> emissions by 31.67% and 29% and PM emissions by 16.33% and 31.78% for WED prepared without surfactant and with surfactant respectively. Alahmer (2013) used water emulsified diesel containing 2% surfactant Tween 20 and 5 to 30% water prepared by electrical blender to run a 4-cylinder, 4-stroke, DI, water cooled diesel engine and observed the engine performance and emission characteristics. They found increase in power generation using WED containing 5% water than base diesel. But, not much difference in power generation was observed using WED having 10% water and diesel only. An 8.31% increase in BTE was observed for emulsion containing 5% water whereas the neat BSFC values were found to be lower for all WEDs compared to pure diesel. They also noted reduction in NO<sub>x</sub> emission using WEDs. Suresh and Amirthagadeswaran (2015) prepared emulsified fuel containing 5 and 10% water using mechanical homogenizer and used in a single cylinder, 4-stroke diesel engine fitted with eddy current dynamometer. They reported increase in brake thermal efficiency and decrease in neat BSFC.

In this experimentally investigated work, authors have compared the two emulsification methods namely, mechanical

homogenization and ultrasonication methods. This comparison is done based on emulsion stability, water particle size, polydispersity index (PDI) and intensity distribution of water particle size in the emulsion. For both methods, 10% water and 2% surfactant mixture of Span 80 and Tween 80 with resultant HLB value 8 have been added to diesel for WED preparation. Two important physical properties namely density and viscosity of the emulsions prepared by both the methods are also measured and compared with those of neat diesel. Finally, a comparative study on the combustion, performance and emission characteristics of a single cylinder, four-stroke, DI, water cooled diesel engine has also been carried out using WEDs prepared by mechanical homogenization and ultrasonication methods.

## 2. Experimental details

The experimental set up, different instruments used and procedure followed in this investigation work have been presented and discussed in this section.

### 2.1. Water emulsified diesel preparation

Surface active materials (surfactant) accumulate at the interfacial space of water droplets and continuous diesel phase and thus stabilize the emulsion (Baskar and Senthil Kumar, 2017). The stability of the emulsion depends on HLB value of the surfactant. Moreover, it has been observed that mixture comprising of one more hydrophilic surfactant and one more hydrophobic surfactant provides better emulsification effect than a single surfactant having intermediate HLB value (Lif and Holmberg, 2006). The mixture of different surfactants often exhibit synergism effect on the properties of a system (Subramanian, 2011). This synergism results in critical micellization concentration and substantially lower interfacial tension than the unmixed surfactant alone. In this work, WEDs have been prepared using both mechanical homogenizer and ultrasonicator using 10% water and 2% surfactant by volume. The surfactant used here is a mixture of two non-ionic surfactants Span 80 (HLB value 4.3) and Tween 80 (HLB value 15). The two surfactants are mixed in such a proportion that the resultant HLB value becomes 8. The resultant HLB value 8 is chosen based on the work of Mondal and Mandal (2016). They mixed Span 80 and Tween 80 in different proportion to get the resultant HLB values 4.3, 6, 8, 9, 10, 11 and 15 and observed that the surfactant mixture having resultant HLB value 8 provides better emulsion stability than other resultant HLB values. The specifications of the surfactants Span 80 and Tween 80 are given in Table 1.

The mechanical homogenizer of REMI Elektrotechnik Ltd., India, model no. RQT-127/D, has been operated at 6000 rpm to prepare WED and this emulsion will now onward be denoted as WED<sub>M</sub>. Ultrasonicator of Sonics vibra cell, USA, model no. VCX 750 has been operated at 80% amplitude and this emulsion will be referred as WED<sub>U</sub> in the rest of this paper. In both the cases, sample processing time is 15 min. Temperature of the emulsion mixture rises during ultrasonication process due to heat spot effect (Lin and Chen, 2006b). This is minimized by keeping the mixture in a cooled water bath during ultrasonication. The schematic diagram of mechanical homogenizer and ultrasonicator are shown in Figs. 1 and 2 respectively.

### 2.2. Measurement of water particle size, PDI and intensity distribution of WEDs

A nanoparticle analyzer, manufactured by OTSUKA Electronics Co, Ltd., Japan, model No. A53878 has been used to measure water particle size and polydispersity index (PDI) of the emulsions

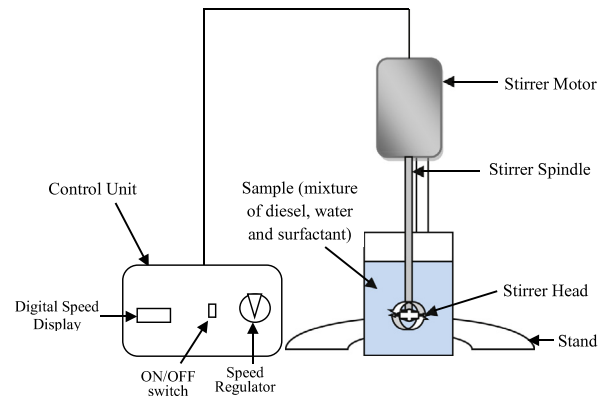


Fig. 1. Schematic diagram of mechanical homogenizer.

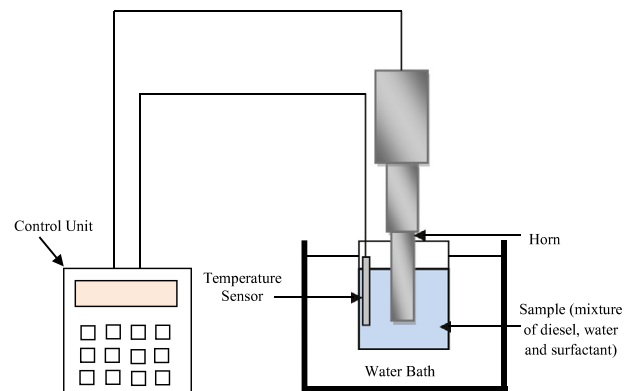


Fig. 2. Schematic diagram of ultrasonicator.

prepared using both mechanical homogenizer and ultrasonicator. It works on the principle of dynamic light scattering (DLS) technique. The intensity distributions of different sized water particles in both types of emulsion are also measured using the nanoparticle analyzer. The number percentage of water particles of different sizes in the emulsion can be obtained from the intensity distribution curve. On the other hand, the homogeneity of the water particle in the sample can be read from the values of PDI.

### 2.3. Emulsion stability and physical property measurement

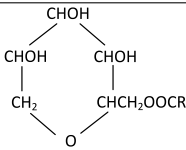
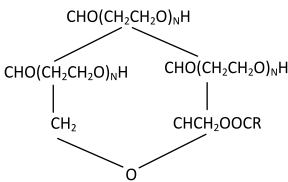
The stabilities of both WED<sub>U</sub> and WED<sub>M</sub> have been measured by keeping the samples undisturbed in two separate graduated centrifuge tubes for a period of two months and noting the separation of water and diesel from the emulsion. The stability has been calculated as:  $(1 - \text{fraction of water and diesel separated}) \times 100\%$  (Mondal and Mandal, 2018; Kojima et al., 2014). The density and the kinematic viscosity of both the emulsions as well as those of base diesel fuel have been measured at 30 °C. A 50 ml volume pycnometer fitted with thermometer which shows the actual temperature of the liquid is used to measure the density. The Ostwald viscometer which works as glass capillary viscometer is used to measure kinematic viscosity following ASTM D445 standard.

### 2.4. Experimental setup for engine study

This experimental investigation has been carried out on a Kirloskar (India) make Model TV1, 4-stroke, single cylinder, direct injection (DI), water cooled diesel engine equipped with an eddy current dynamometer. The compression ratio and the



**Table 1**  
Specification of the surfactant used for this investigation.

Surfactant type	Chemical name	HLB value	Appearance	Specific gravity	Chemical structure
Span 80	Sorbitan monooleate	4.3	Brown viscous liquid	0.98	
Tween 80	Polyoxyethylene sorbitan monooleate	15	Amber sticky liquid	1.08	

**Table 2**  
Gas analyzer specification (Testo 350 flue gas analyzer).

Parameters	Resolution	Accuracy	Range
CO	1 ppm	$\pm 10 < 200$ ppm	0–10,000 ppm
CO <sub>2</sub>	0.01 vol%	$\pm 0.3% < 25$ vol%	0–50 vol%
NO	1 ppm	$\pm 5% \text{ reading} < 2000$ ppm	0–3000 ppm
NO <sub>2</sub>	0.1 ppm	$\pm 5% < 100$ ppm	0–500 ppm
O <sub>2</sub>	0.01 vol%	$\pm 0.2$ vol%	0–25 vol%
HC	1 ppm	$\pm 10%$ of reading	0–40,000 ppm

**Table 3**  
Smoke meter specification (Indus OMS 103 smoke meter).

Parameters	Resolution	Accuracy	Range
HSU	0.1%	–	0–99.9
K	0.01 m <sup>-1</sup>	$\pm 0.1$ m <sup>-1</sup>	0–∞

fuel injection timing are 17.5:1 and 23 °C before TDC respectively. The bore and the stroke of the engine are 87.5 mm and 110 mm respectively. It is fitted with a three-holed (hole diameter 0.3 mm) fuel injector which injects the fuel at a pressure of 210 bar. The schematic diagram of the experimental setup with all accessories is shown in Fig. 3. The setup is well equipped with necessary devices to measure the in-cylinder pressure with respect to crank angle. The engine is loaded by means of an eddy current water cooled dynamometer. The fuel flow is measured using differential pressure transmitter of Yokogawa, model no: EJA110A-EMS-5A-92NN. The cylinder pressure is measured by a piezoelectric pressure sensor of PCB Piezotronics, Inc, Model: HSM111A22. This pressure sensor is fitted to the cylinder head of the engine. All the combustion and performance related data are generated using Lab-VIEW based software “EnginesoftLV” through a laptop which is directly connected to the electronic data acquisition system of the test engine setup. The engine is operated at constant speed of 1500 rpm and at different loads to analyse the combustion, performance and emission characteristics. The emissions of NO<sub>x</sub>, CO and HC have been measured using a Testo 350 flue gas analyzer; whereas the smoke emission has been recorded with the help of Indus OMS 103 smoke meter. The exhaust gas of the engine is allowed to rush forward through the probe inserted at the tail pipe of the engine to record the emission data. The specification of the gas analyzer and smoke meter are given in Tables 2 and 3 respectively.

### 3. Result and discussion

The parameters recorded from this experimental work as mentioned in the previous section have been presented and discussed in details in this section. The water particle sizes, PDI, stability and physical properties of the WEDs prepared by

ultrasonicator and mechanical homogeniser indicate the physical behaviour of the respective fuel. The combustion, performance and emission characteristics of the engine using prepared emulsions as well as base diesel have been presented graphically and discussed in the following subsections for investigating and comparing the said fuels.

#### 3.1. Water droplet size and PDI

In the mechanical homogenization process, the liquid mixture of diesel, water and surfactants is violently agitated by means of a stirring head which is fitted with a set of blades. At high speed operation, a large shearing and cutting force is generated among the interfaces of the immiscible liquids and it causes the emulsification (Lin and Chen, 2008). On the other hand, when violent ultrasonic waves at a rather high frequency are applied by ultrasonicator, strong physical and chemical reaction can take place in the liquid mixture. In ultrasonication process, large amount of energy is released, which is transferred to the liquid mixture thereby generating a stronger mechanical stirring effect. Thus two immiscible liquids can be transformed into much more homogeneous emulsion. During ultrasonication process heat is generated in the emulsion due to heat spot effect (Lin and Chen, 2006b; Li et al., 2002).

The PDI value indicates the heterogeneity of sizes of molecules or particles in a mixture. Thus it is also called the heterogeneity index (Jiang et al., 2014). Lower value of PDI of an emulsion indicates more homogeneity of the water particles. The dynamic light scattering technique is not suitable for the emulsion whose PDI value is higher than 0.7 i.e. the sample has a very broad size distribution.

The average droplet sizes of the water particles of both WED<sub>U</sub> and WED<sub>M</sub> and their respective PDI values are shown in Table 4. It can be seen from the table that the emulsified diesel prepared using ultrasonication process contains much smaller sized (508.5 nm) water droplets than that in the emulsion prepared using mechanical homogenization process (952.5 nm). The PDI value is also found to be much lower (0.125) for WED<sub>U</sub> than that of WED<sub>M</sub> (0.275). This indicates that the emulsion prepared by ultrasonic machine is having more uniformity in water particle size distribution than the emulsified diesel prepared by the mechanical homogenization machine. In other words, water particle size in WED<sub>U</sub> varies over a narrow range and the average value is 508.5 nm. Whereas, water particle size in WED<sub>M</sub> varies over a broader range and the average value of the same is 952.5 nm. The ranges of water particle size for WED<sub>U</sub> and WED<sub>M</sub> have been discussed in details in next section of this article. So, the ultrasonic waves produced by an ultrasonication process can be considered more effective than that of cutting and shearing force

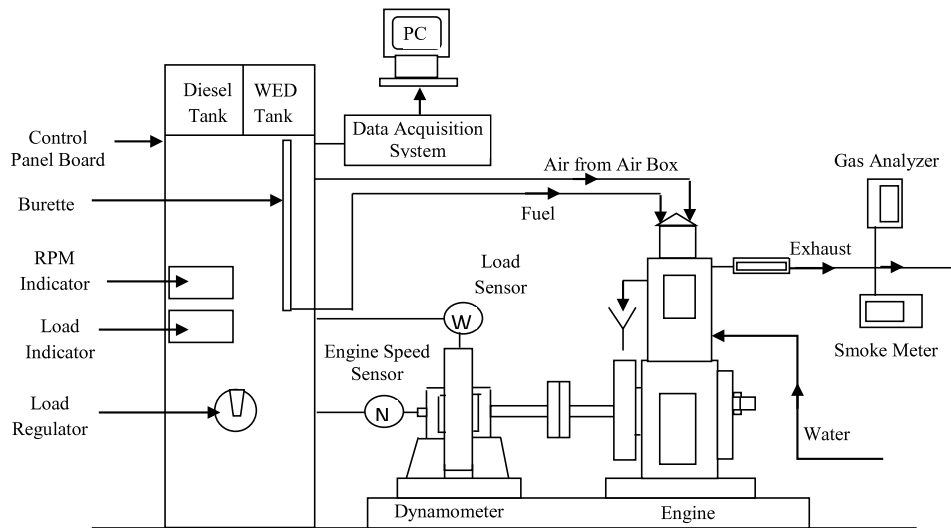


Fig. 3. Schematic diagram of the experimental setup.

Table 4

Average droplet size of the water particle and PDI of different fuels.

Type of fuel	Avg. droplet size	Polydispersity Index (P.D.I.)
WED <sub>U</sub>	508.5 nm	0.125
WED <sub>M</sub>	952.5 nm	0.275

generated in mechanical homogenization process in respect of water particle size and homogeneity of the emulsion. Maiboom and Tauzia (2011) prepared water emulsified diesel containing 20% water and 2% surfactant mixture of Span 80 and Tween 80 with resultant HLB value 6.5 using mechanical homogenizer. They measured the average water particle size using microscope to be of about 40  $\mu\text{m}$ . In the present work, average water particle size in the emulsion prepared using mechanical homogenizer containing 10% water and 2% surfactant mixture of Span 80 and Tween 80 with resultant HLB value 8 is found to be 952.5 nm. Though the water content in this emulsion is half of that prepared by Maiboom and Tauzia (2011), the average water particle size (less than 1  $\mu\text{m}$ ) is much lower than that observed by them (40  $\mu\text{m}$ ). On the other hand, Gong and Wei-Biao (2001) prepared WED containing 40% of water by volume and 2–3 drops of Tween 80 as surfactant using an ultrasonicator. They reported the average water droplet sizes of 10  $\mu\text{m}$ . The emulsion prepared for the present work containing 10% water and 2% surfactant mixture using ultrasonicator has average water particle size much lower (about 0.5  $\mu\text{m}$ ) than that reported by Gong and Wei-Biao (2001). The above comparisons indicate that emulsification methods and quantity of water and surfactant which have been chosen for this experimental work may be better than those mentioned above. The primary reason for these differences in water particle size is the amount of water added to diesel during the emulsification process.

### 3.2. Intensity distribution

The intensity size distributions, displayed as intensity histograms in Fig. 4(a) and (b), are directly measured by the nanoparticle analyzer. Intensity histograms are based upon the intensity of light scattered by the water particles present in the emulsion. Thus, in these histograms, the magnitude of each peak is proportional to the percent of the total scattered intensity due to particles. It can be observed from Fig. 4(a) that the differential intensity for WED<sub>M</sub> varies from 0.3% for 168 nm water particle

size to 0.4% for 6878 nm water particle size with intensity peak is only 3% for 1076 nm particles size. This indicates broadness in water particle size with presence of bigger particle size as much as 6.878  $\mu\text{m}$ . The corresponding values for WED<sub>U</sub> are 0.5% for 246 nm particle size and 0.6% for 1186 nm water particle size with intensity peak is 6.9% for 541 nm as shown in Fig. 4(b). This means, much narrower in water particle size range is present in the emulsion prepared by ultrasonicator. Thus the emulsion produced by mechanical homogenization process contains bigger and wider range of water particle sizes than those prepared by ultrasonication process.

### 3.3. Emulsion stability

The stability profiles of the emulsions prepared by mechanical homogenizer and ultrasonicator are shown in Fig. 5. For better understanding, the stability behaviour of both types of emulsion are presented in expanded form in the same graph for up to 80 h. It can be clearly observed from the figure that up to about 45 h there is no sign of any instability, i.e., no separation in the emulsion WED<sub>U</sub>, whereas the corresponding value for the WED<sub>M</sub> is only 15 h. After 15 h, stability of the emulsion WED<sub>M</sub> reduces very fast as shown in the figure. It can also be seen from the figure that after four days, WED<sub>U</sub> shows about 98% stability whereas WED<sub>M</sub> shows 89% stability. After 10 days, the corresponding values of stability are found to be 97% and 84% respectively and after one month those values are found to be 92% and 75% respectively. Coalescence and Ostwald ripening are considered as the two main probable reasons of separation or break down process in the emulsion system (Noor El-Din et al., 2013; Porras et al., 2008; Uson et al., 2004). The process in which water droplets come in close position and combine to each other to form a larger water droplet is called coalescence. In Ostwald ripening mechanism, molecular diffusion of smaller water droplets takes place through the continuous oil phase to grow the larger water droplets. According to Lifshitz–Slyozov and Wagner (LSW) theory (Noor El-Din et al., 2013; Uson et al., 2004), the Ostwald ripening rate is proportional to the cube of the radius of water particle. That means the Ostwald ripening rate for WED prepared by ultrasonicator will be far less than the WED prepared by mechanical homogenizer as the particle size in the first case is much lower. Porras et al. (2008) and Uson et al. (2004) concluded that Ostwald mechanism is mainly responsible for the instability of the emulsion. Thus lower water particle size and PDI in case of WED<sub>U</sub> are the reasons behind its higher stability over the emulsion prepared using mechanical homogenizer.

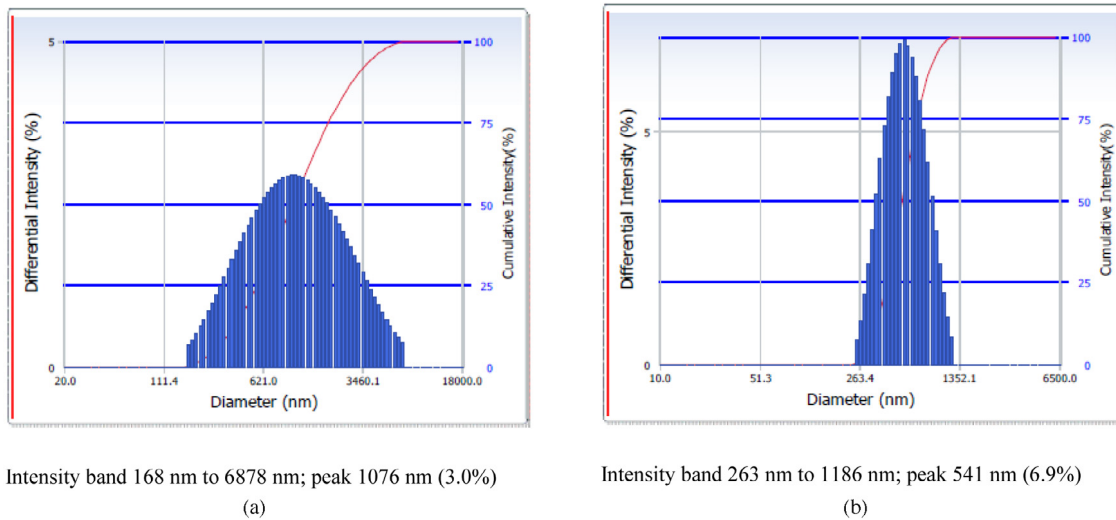


Fig. 4. Intensity size distributions histograms for (a) WED<sub>M</sub> and (b) WED<sub>U</sub>.

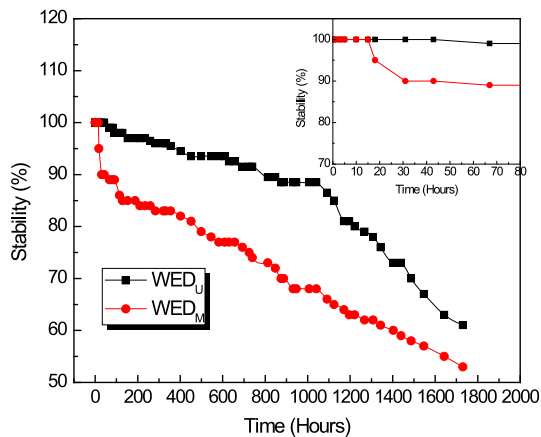


Fig. 5. Stability profile of the emulsion prepared by ultrasonicator and mechanical homogenizer.

#### 3.4. Changes in density and viscosity

Densities for both types of prepared emulsion are found to be the same ( $840.7 \text{ kg/m}^3$ ), but it is higher than that of the base diesel ( $823.1 \text{ kg/m}^3$ ). This can be attributed to the addition of higher density water to the lower density diesel fuel. The increase in density of fuel has some beneficial effects. The higher density adds additional momentum, so fuel jet travels more distance and air-entrainment in the spray increases which improves air-fuel mixing resulting in better combustion (Lin and Chen, 2006b; Ivanov and Nevedov, 1965). The viscosities of the WEDs are also observed to be higher than that of the base diesel (2.979 cSt). Also, the viscosity of WED<sub>U</sub> (3.322 cSt) is noted to be slightly higher than that of WED<sub>M</sub> (3.282 cSt). The increase in viscosity is due to the frictional force and the generated static electricity among the disperse water droplets and continuous diesel fuel (Pariotis et al., 2006; Kojima et al., 2014). Frictional force and static electricity generation are more in case of emulsion prepared by ultrasonicator due to smaller water droplet size. Kojima et al. (2014) also concluded that the decrease in water particle size led to more water surface area resulting higher viscosity. Armas et al. (2005) experimentally investigated the engine performance of a Renault F8Q, four-cylinder, turbocharged diesel engine and observed that increase in viscosity for emulsified diesel resulted

earlier fuel injection compared to base diesel. They attributed this to the changes in the dynamics of the fuel system because of flow variation which depends on viscosity variation. However, they reported more ignition delay for WED and thus the beginning of the heat release was found to be almost same. So, the advancement in injection timing allows much more air-fuel mixing time (Armas et al., 2005; Tarlet et al., 2010).

#### 3.5. Combustion characteristics

In diesel engine, both physical and chemical processes of the injected fuel take place before any significant amount of chemical energy is released due to combustion (Heywood, 1988). The fuel is injected into the combustion chamber towards the end of the compression stroke and it is followed by atomization, vaporization, fuel-air mixing and finally the combustion of the injected fuel. This type of engine always operates with lean fuel/air mixture having equivalence ratio less than one. So, the effective value of the adiabatic index,  $\gamma$  over the expansion process is higher than that of other types of internal combustion engine (Heywood, 1988). This results in higher fuel conversion efficiency in diesel engine.

The combustion characteristics of the diesel engine running at constant speed and full load conditions using pure diesel as well as emulsified diesel have been examined and compared. Two main combustion characteristics namely, net heat release rate and in-cylinder pressure have been considered for investigation in this work and their variations with crank angle are shown in Figs. 6 and 7 respectively.

The period of time from start of fuel injection to beginning of combustion is referred as ignition delay. Heat release starts with the beginning of combustion of fuel. Fig. 6 indicates about 4% higher peak heat release rate for WED<sub>U</sub> than that with pure diesel. The figure also clearly indicates longer ignition delay for emulsified diesel. At the beginning of the combustion, the combustion chamber temperature is low where micro-explosion is not so significant as its intensity increases with the increase of temperature (Mondal and Mandal, 2018). Heat sink effect also reduces in-cylinder temperature. Higher viscosity of the WED also affects the fuel atomization (Tarlet et al., 2010). The combined effects of these retard the atomization, evaporation and subsequently formation of combustible mixture. Thus a longer ignition delay is observed in case of emulsified fuel when more fuel would be physically prepared for chemical reaction and this

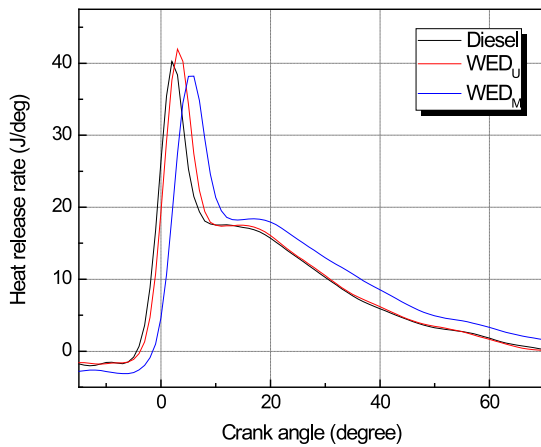


Fig. 6. Comparison of net heat release rate with WEDs and diesel.

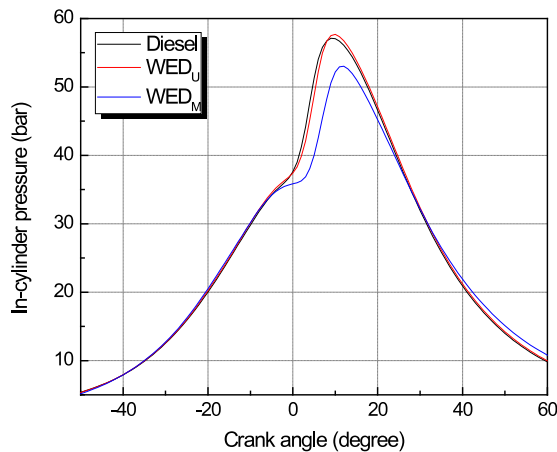


Fig. 7. Comparison of In-cylinder pressure with WEDs and diesel.

promotes partial premixed combustion (Lin and Chen, 2006a). The extent of violent micro-explosion is enhanced with WED having smaller water droplets which are more uniformly distributed in the dispersed diesel phase (Lin and Chen, 2008). This may promote the early beginning of combustion for WED<sub>U</sub> than WED<sub>M</sub> as the ultrasonication produces more uniform and smaller water droplets than mechanical homogenization. The more violent micro-explosion accelerates efficient and more complete combustion in case of emulsion prepared by ultrasonicator. Thus higher peak heat release rate is observed for WED<sub>U</sub> than pure diesel. But, the peak heat release for WED<sub>M</sub> is less than that with pure diesel because micro-explosion is not so effective in case of WED<sub>M</sub>.

Though the heating values of both WED<sub>U</sub> and WED<sub>M</sub> are less than base diesel, a slightly increase in in-cylinder pressure has been observed for WED<sub>U</sub> compared to base diesel as shown in Fig. 7. More complete combustion, as discussed above, of the emulsified diesel prepared by ultrasonicator is the reason behind it. Thus the effect of micro-explosion along with promoted premixed combustion due to ignition delay accelerates the combustion process for WED<sub>U</sub>. The net heat release rate and peak in-cylinder pressure for WED<sub>M</sub> are noted to be about 5% and 7% lower, respectively, than those with base diesel. This may be attributed to the lower heating value of WED<sub>M</sub> compared to that of pure diesel.

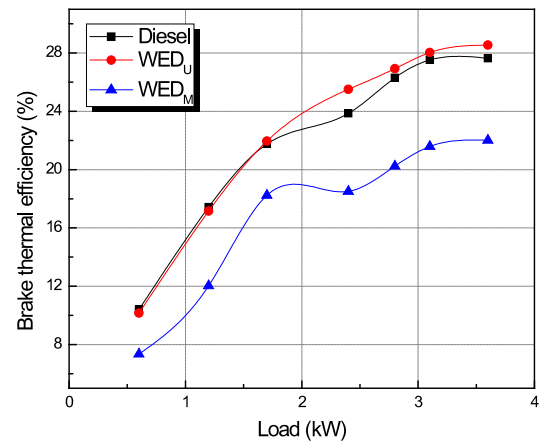


Fig. 8. Comparison of brake thermal efficiency with WEDs and diesel.

### 3.6. Performance characteristics

Two major important parameters namely, BTE and BSFC have been discussed in this section to analyse the performance characteristics of diesel engine using emulsified fuel as well as pure diesel. The variation of torques with fuel consumption for all the tested fuels have also been discussed. The ratio of brake power produced to the amount of heat input to the engine in unit time is called brake thermal efficiency. The effect of more intense micro-explosion for WED<sub>U</sub> than WED<sub>M</sub> can also be observed in BTE graph of the engine. Fig. 8 shows the variation of BTE with load for three types of tested fuels. It can be seen from the figure that the efficiency increases with the increase of load which can be attributed to the improved combustion at higher load. The figure also indicates slightly lower BTE for WED<sub>U</sub> at low load and it is marginally higher at higher load than pure diesel. The higher combustion chamber temperature and pressure at higher load enhance the micro-explosion resulting in more complete combustion of the emulsified fuel (Tanaka et al., 2006; Fu et al., 2008). Though the heating value of WED<sub>U</sub> is less than that of pure diesel, the combined effect of higher heat release rate and higher peak in-cylinder pressure results in higher BTE at higher load than the pure diesel. On other hand, the BTE using WED<sub>M</sub> is much less at all loading conditions. This can be attributed to the lower heat release rate and lower peak in-cylinder pressures due to less effective micro-explosion with higher water particle size in the emulsion. The lower heating value of WED<sub>M</sub> and heat sink effect due to evaporation of water present in the emulsion are also the reasons behind this lower efficiency. At full load, the BTE with WED<sub>U</sub> is noted to be about 3% higher than the base diesel. On the other hand, the corresponding value using WED<sub>M</sub> as fuel is found to be 20% lower than the base diesel.

The variations of another important engine performance parameter, BSFC with load using pure diesel and both types of emulsified diesel have been shown in Fig. 9. The fuel mass consumption rate to the unit brake power output is called BSFC. It measures that how efficiently the engine is converting supplied fuel energy to produce work. The inferior combustion characteristic of fuel is indicated by its higher BSFC value. The figure shows that the BSFC decreases with the increase in load. This can be attributed to the higher total energy release at higher engine load, though the loss of frictional power remains almost the same (Alahmer, 2013). Thus the net power output increases and the specific fuel consumption rate decreases. At higher load, the in-cylinder temperature and pressure are higher which improve the fuel combustion efficiency. This can also be considered as one



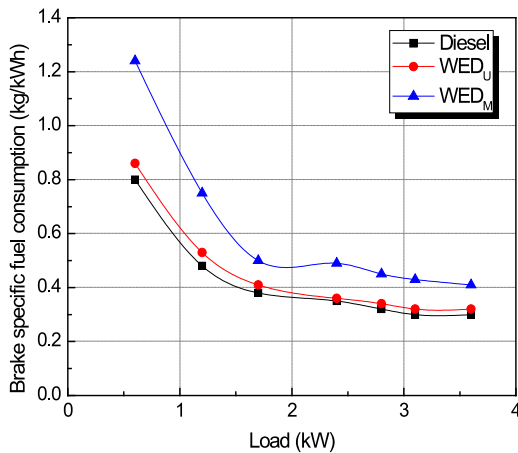


Fig. 9. Comparison of brake specific fuel consumption with WEDs and diesel.

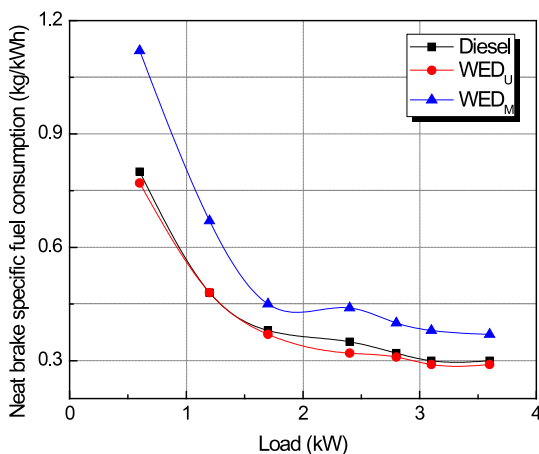


Fig. 10. Comparison of neat brake specific fuel consumption with WEDs and diesel.

of the reason for lower BSFC at higher load. The figure also clearly indicates higher BSFC for emulsified fuels than pure diesel at all loads. As some amount of diesel are displaced by equal amount of water in case of WED, the heating value of emulsion gets lowered resulting higher fuel consumption rate. The variations of neat BSFC with engine load are presented in Fig. 10 considering only the amount of diesel present in the fuel. It can be noted from the figure that the neat BSFC using WED<sub>U</sub> is slightly lower than that with base diesel whereas the same is higher when WED<sub>M</sub> is used as fuel. In case of WED<sub>U</sub>, the enhanced micro-explosion due to uniformly distributed tiny water particles overcomes the limitation of lower heating value of the fuel.

The variations of torque with fuel consumption using both types of emulsified diesel and base diesel have been shown in Fig. 11. The figure clearly indicates that the torque generated using WED<sub>U</sub> is slightly less than that with base diesel, whereas, the same is much lower when WED<sub>M</sub> is used. It shows that conversion of chemical energy of fuel into useful mechanical work is better for WED<sub>U</sub> than WED<sub>M</sub>. It can also be stated that though the heating value of both WED<sub>U</sub> and WED<sub>M</sub> are same and lower than base diesel, the enhanced micro-explosion of WED<sub>U</sub> results in improved combustion. Consequently, more torque is generated in case of WED<sub>U</sub> compared to WED<sub>M</sub>.

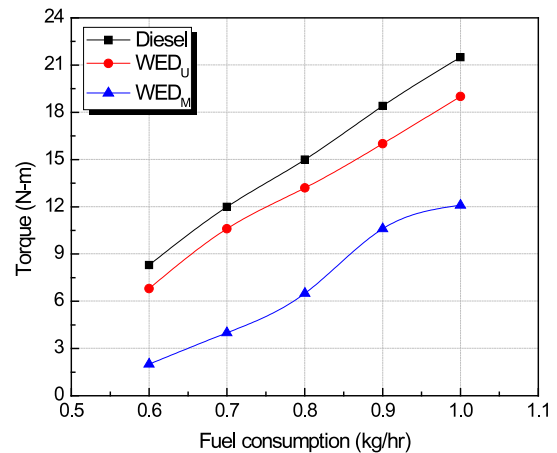


Fig. 11. Comparison of torque with WEDs and diesel.

### 3.7. Emission characteristics

In diesel engine, the pollutant formation is strongly dependent on the fuel distribution in the cylinder and also on the changes of that distribution due to mixing (Heywood, 1988). Three most harmful pollutants namely, NO<sub>x</sub>, CO and smoke have been addressed in this section. Though nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>) are collectively referred to as NO<sub>x</sub>, NO is the predominant oxide of nitrogen generated in the diesel engine cylinder (Heywood, 1988; Mondal and Mandal, 2019). The variation of NO<sub>x</sub> emission with load is presented in Fig. 12. It shows that the concentration of NO<sub>x</sub> is increased with the increase of engine load. Burning of higher amount of fuel at higher load causes higher combustion chamber temperature. This creates favourable condition for more NO<sub>x</sub> formation. However, NO<sub>x</sub> emission is lower for emulsified diesel than those with base diesel at all loading conditions. The NO<sub>x</sub> is mainly formed through oxidation of nitrogen present in the air. NO<sub>x</sub> formation is mostly temperature dependent and it increases with the increase in combustion chamber temperature (Alahmer, 2013; Weibiao et al., 2006). The heat sink effect due to evaporation of water present in the emulsion reduces the combustion chamber temperature by absorbing sensible heat and latent heat for evaporation. It can further be noted that the NO<sub>x</sub> emission is slightly less for WED<sub>M</sub> than WED<sub>U</sub>. The maximum and the average reductions in NO<sub>x</sub> emission using WED<sub>M</sub> as fuel are 77.5% and 36.7% respectively compared to those with base diesel. The corresponding values for WED<sub>U</sub> are 75.5% and 32.6% respectively. This can be attributed to the slightly higher burning gas temperature of WED<sub>U</sub> resulting from improved combustion compared to WED<sub>M</sub> (Lin and Chen, 2008).

In CI engine, CO formation is primarily controlled by the fuel/air equivalence ratio (Heywood, 1988). The ratio of actual fuel/air ratio to stoichiometric fuel/air ratio is defined as the fuel/air equivalence ratio. Since, diesel engine normally operates in the leaner side of stoichiometric, so CO emission is very less in this case. The variations of CO emission with load for WEDs as well as normal diesel are shown in Fig. 13. CO is formed due to incomplete combustion of fuel. Further oxidation of CO to CO<sub>2</sub> reduces the CO emission. A higher combustion chamber temperature accelerates the oxidation rate of CO. In accordance with that, the figure indicates decrease in CO emission with the increase of engine load as the combustion chamber temperature increases at higher load. The figure also shows that the CO emission is higher for emulsified diesel than that with pure diesel. This can be attributed to the lower combustion chamber temperature due to

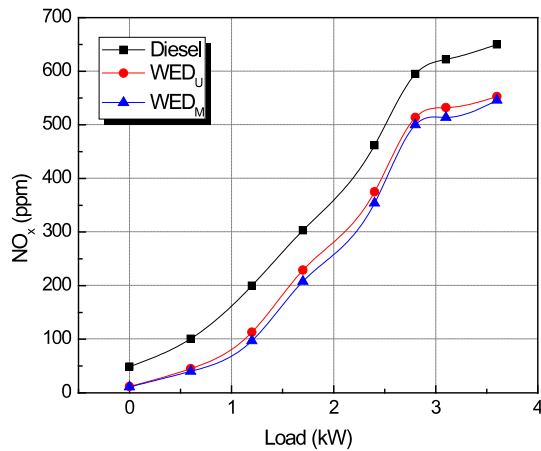


Fig. 12. Comparison of  $\text{NO}_x$  emission with WEDs and diesel.

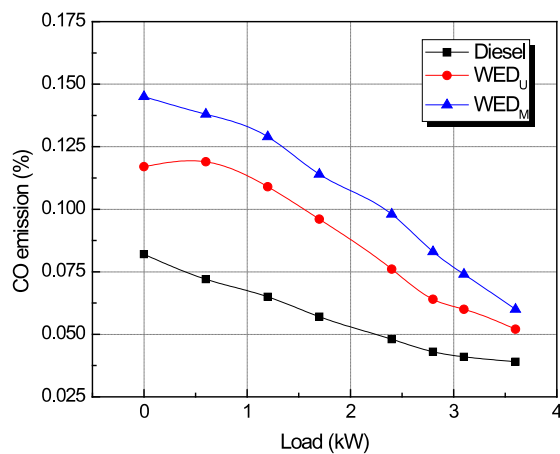


Fig. 13. Comparison of CO emission with WEDs and diesel.

heat sink effect in case of emulsified diesel. It can further be noted from the figure that the CO emission is lower for WED<sub>U</sub> than that with WED<sub>M</sub>. This can be explained by improved combustion of WED<sub>U</sub>, which causes a higher in-cylinder temperature.

The formation of smoke is reduced with the improvement of fuel combustion and vice versa. The variations of smoke emission with load for base diesel and both types of emulsified diesel are shown in Fig. 14. The smoke emission increases with the increase of load for all tested fuels. This is due to the burning of higher quantity injected fuel at higher load. It can also be noted from the figure that the smoke emission is lower for emulsified diesel than that with base diesel. This may be attributed to improved combustion of WED due to the combined effects of secondary atomization resulting from micro-explosion, more intense pre-mixed combustion due to ignition delay and more air-entraining due to higher injected fuel jet momentum. One can also observe from the graph that the use of WED<sub>U</sub> produces less smoke than that with WED<sub>M</sub>. The average reduction in smoke emission using WED<sub>U</sub> and WED<sub>M</sub> compared to base diesel are 49.8% and 45.2% respectively. Improved combustion due to more effective micro-explosion with lower water particle sized emulsion produced by ultrasonicator may be the reason behind this reduction.

#### 4. Conclusion

On the basis of results obtained during this experimental investigation, the following conclusions can be drawn:

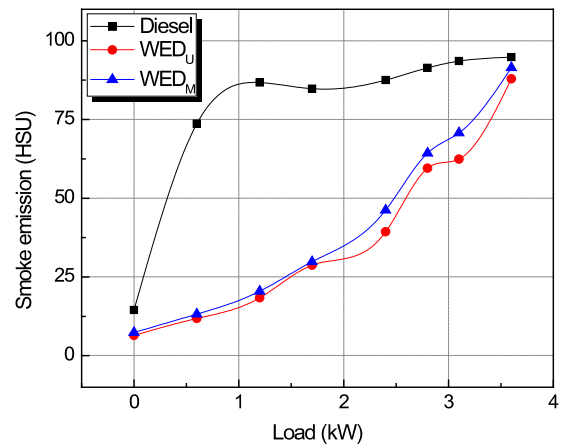


Fig. 14. Comparison of smoke emission with WEDs and diesel.

- Water particle size and PDI are found to be lower for the emulsion prepared using ultrasonicator than that prepared using mechanical homogenizer.
- Hundred percent stability, i.e., zero separation have been observed up to 45 h and 15 h for the WEDs prepared using ultrasonicator and mechanical homogenizer respectively. After one month, stability is noted to be 92% for the WED<sub>U</sub> against 75% for WED<sub>M</sub> because of lower water particle size and lower PDI in case of former one.
- Improved combustion characteristics are observed for the WED<sub>U</sub> due to more uniform and smaller water droplets produced in ultrasonication method which results in violent micro-explosion. Use of WED<sub>U</sub> indicates 4% higher heat release rate than that with base diesel and the same is found to be 5% lower when WED<sub>M</sub> is used instead of base diesel.
- Higher brake thermal efficiency is observed using emulsion prepared by ultrasonicator whereas, it is noted lower for the same prepared by mechanical homogenizer in comparison to base diesel. Net BSFC is observed to be lower for WED<sub>U</sub> compared to the diesel only operation.
- Emissions of  $\text{NO}_x$  and smoke are found to be significantly lower for both types of emulsions than those with base diesel due to heat sink effect and micro explosion phenomenon respectively. But,  $\text{NO}_x$  emission is observed slightly higher and smoke emission is noted marginally lower for WED<sub>U</sub> than those with WED<sub>M</sub>.

Finally, it can be concluded that the ultrasonication is far better method than mechanical homogenization with respect to the preparation of water emulsified diesel to be used as CI engine fuel.

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#### Declaration of competing interest

None.

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