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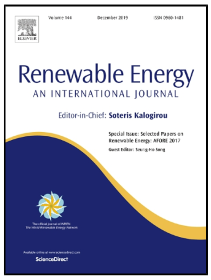

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An experimental study on performance and emission characteristics of an IDI diesel engine operating with neat oil-diesel blend emulsion

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ABSTRACT

Stable neat oil emulsions were prepared and tested in a multi-cylinder engine to assess the exhaust emission and performance characteristics. The heating value of the biofuel-diesel blend emulsion was 16.8% higher than neat rapeseed oil and 6.7% lower than neat diesel fuels. The density of the biofuel emulsions were increased by up to 11% as compared to neat fossil diesel. The engine produced similar power output when emulsified fuels were used instead of fossil diesel. At full load, the thermal efficiency of neat biofuel emulsion was 12% higher than that of fossil diesel. At higher loads, the bsfc of the biofuel blend emulsion was very close to that of fossil diesel. Compared to fossil diesel, emulsified fuels gave slightly higher CO_2 emissions. Biofuel and biofuel-diesel blend emulsions produced up to 15% lower NOx emissions. At 100% load, the smoke intensity of biofuel blend emulsion was about 29% lower than neat fossil diesel operation. Emulsified fuels combusted well, and at higher loads produced similar exhaust gas temperatures to those in neat fossil diesel operation. The study concluded that neat oil - diesel - water emulsion fuel could be used in an unmodified diesel engine for increased thermal efficiency and decreased emissions.

***Keywords*: Biofuel blend; CI Engine; Emission; Emulsification; Performance; Water.**

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Abbreviations

B100	100% Biodiesel
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CI	Compression Ignition
CNG	Compressed Natural Gas
DI	Direct Injection
DW	Distilled Water
E1	Emulsion 1: 95.5% RO + 2.5% DW + 2% SF
E2	Emulsion 2: 95.5% FD + 2.5% DW + 2% SF
E3	Emulsion 3: 80.5% FD + 15% RO + 2.5% DW + 2% SF
E4	Emulsion 4: 78% FD + 15% RO + 5% DW + 2% SF
EGR	Exhaust Gas Recirculation
EU	European Union
FD	Fossil Diesel
100 FD	100% Fossil Diesel
GHG	Greenhouse Gas
HLB	Hydrophilic-Lipophilic-Balance
IC	Internal Combustion
IDI	Indirect Injection
LNG	Liquefied Natural gas
PM	Particulate Matter
PN	Particle Number
RO	Rapeseed Oil
100 RO	100% Rapeseed Oil
SF	Surfactant
SFC	Specific Fuel Consumption
SMD	Sauter Mean Diameter
UK	United Kingdom

1. Introduction

In 2016, the world average daily demand of oil and liquid fuel was 96 million barrels (approximately 35 billion barrels/year) [1]. Oil demand will continue to grow until 2040 [2]; the global oil demand is expected to increase to 98 million barrels/day in 2017 [3], and forecasted to reach to 103.5 million barrels/day by 2040 [2]. Due to the huge consumption of the fossil based fuels the emissions of greenhouse gases (GHG) are increasing alarmingly. The world total GHG emission in 2010 was 49 Gt CO_2-eq. and 65% (32 Gt CO_2-eq.) of the total emissions came from fossil based fuels [4]. As a consequence of the high level of GHG emissions, the Earth's mean temperature was increased by 0.85^0C between 1880 and 2012 [4].

In addition to the impact on the environment, the GHG emissions also affect the health and wellbeing of living beings. For example, air pollution is linked to various diseases such as cancer, asthma, stroke and heart disease, diabetes, obesity, and changes linked to dementia [5]. Exposure to pollutants cause an equivalent to 40,000 early deaths a year in the United Kingdom (UK); resulting to about £20 billion expense every year [5]. More specifically, pollutants such as NO_2 gas and particulate matter (PM) emissions cause an equivalent to 23,500 and 29,000 premature deaths in the UK respectively [6].

Fossil based liquid fuels are widely used for mobility and stationary power generation. The mobility or the transport sector is the second largest source of carbon pollution in most countries in the world [7]. For example, in the European Union (EU), the transportation sector alone accounts for 23% of air pollution [8]. Internal combustion (IC) engines are widely used in the transportation sector. Researchers are working on various ways how to reduce the GHG emissions from IC engines, including electrification, hybridisation, use of compressed natural gas (CNG) and liquefied natural gas (LNG), novel combustion concepts, and the use of renewable liquid fuels. Renewable biofuels could potentially replace considerable amount of fossil fuels currently used in the transport sector and offset GHG emissions. Biofuels sourced from various resources are being experimented with both in modified and in unmodified engines, either in the form of blending or as pure (ie. 100% biofuels) [9] [10] [11] [12] [13] [14]. However, due to high viscosity and materials compatibility issues, use of 100% biofuel (e.g. neat biodiesel) may affect combustion characteristics and engine lifetime; hence, either modifications to the engine or upgradation of the biofuels properties are recommended [15] [16] [17]. Blending biofuels with fossil diesel is a well-known practice and could reduce the consumption of fossil diesel substantially. Blending can avoid the need for engine modifications that could be expensive and difficult for engine manufacturers to justify, until a stable market is established. Furthermore, blending biofuels with fossil diesel and additives could help in improving the engine performance and reducing the tail pipe emissions. Yilmaz and Atmanli [10] conducted a study on a 4 cylinder indirect injection (IDI) engine operating with diesel-biodiesel-pentanol blends. They reported that the dilution with pentanol gave reduced exhaust gas temperature and NOx emissions in comparison to using either fossil diesel or waste cooking oil biodiesel alone (i.e. without pentanol additives). The quantity of pentanol additives used by the authors consisted of 5%, 10% and 20% in volume concentrations [10]. Jatropha oil was tested in the engine both as pure and also as blends [13, 14]. Up to 10% concentration of Jatropha oil with fossil diesel fuel showed similar thermal efficiency when compared to pure fossil diesel operation [14]. Preheated Jatropha oil performed better, but NOx emissions were increased [13, 14].

Water emulsification is another technique which could be used to improve IC engine performance and reduce exhaust pollutants [18] [19] [20] [21] [22]. Water can be added via emulsified fuel, in-cylinder injection, injection into the air intake manifold, or injection into the exhaust manifold. Injecting water either in the intake or exhaust manifold system requires engine component modifications. Injecting water in the combustion chamber requires a separate injector and might affect lubrication of the cylinder liner-piston ring. In contrast, emulsification avoids the need for such modifications. Water is suspended in the fuel with the help of a surfactant; hence, water does not directly come into contact with the engine surfaces. Evaporation of the doped water molecules leads to micro-explosion phenomenon for improved combustion and reduced emissions. Addition of the water in fossil diesel fuel can improve thermal efficiency; and decrease the NOx emissions, formation of soot and carbonaceous residues [22] [23] [24] [25] [26]. The NO_x and soot emissions were decreased by 85% and 40% respectively when both exhaust gas recirculation (EGR) and water injection (in the exhaust manifold) techniques were applied [24]. The emulsion method gave higher NO and PM reduction than the injection method, when both water-diesel emulsions and water injection into the inlet manifold techniques were applied separately in a direct injection diesel engine under similar operating conditions [27]. Furthermore, another study reported that injecting water into the air manifold gave longer ignition delay and reduced in-cylinder pressure and temperature [28]. Abu-Zaid [20] reported that 20% water in fossil diesel emulsion increased the thermal efficiency of the compression ignition engine by approximately 3.5% compared to only fossil diesel operation. Lif and Holmberg [29] reported that water-diesel emulsion helped to decrease the NOx and PM emissions; however, on the other hand, the use of the water-diesel emulsified fuel led to increased HC and CO emissions.

The stability of the water emulsion in fossil diesel was examined using hydrophilic-lipophilic-balance (HLB) value of the surfactant composition [30]. The stable emulsions were then injected and tested in a pre-burn constant volume chamber, the ignition delay was longer compared to pure fossil diesel operation [30]. Water in diesel emulsified fuels gave reduced torque with no significant changes in the specific fuel consumption, the smoke emission was also decreased [31]. Surfactant free fossil diesel emulsions were produced using a real time mixer and tested successfully in an automobile engine [32]. The study reported that NOx and smoke emissions were reduced, fuel consumption was decreased by 8.56% when 6.5% water was added in diesel fuel [32]. Hasannuddin et. al. [33] reported that water in diesel fuel gave higher CO emission due to the lower exhaust gas temperature than that of diesel. They reported that up to 10% water in diesel can be used in the diesel engine for better performance and reduced emissions [33]. Another study reported that fossil diesel - water emulsions decreased NO_x, PM and exhaust temperature by 54.40%, 15.47% and 25.00% respectively [34]. The emulsified fuels produced lower carbon deposits on piston crown, cylinder head and injector tip than neat fossil diesel operation [34]. The ignition delay was prolonged and soot emission was significantly reduced as the water content in the fossil diesel emulsion was increased [35]. The kinematic viscosity and density of the diesel-water emulsions increased with increasing water content [36]. Up to 2% water in diesel increased engine output power when compared to pure diesel operation [36]. The water droplet sizes in the emulsions affected engine performance and emissions characteristics, emulsion with smaller water droplet sizes led to higher NOx emissions when compared to emulsion with larger droplet sizes [37]. Smaller water droplet sizes increased the contact surface area between fuel and water and led to increased thermal efficiency by up to 20% when compared to that of fossil diesel [37].

Most emulsion studies found in the literature concentrated on using fossil diesel. Recently, researchers have started exploring the impact of biofuel emulsions on engine performance and emission. Carboxymethylated wood lignin was used as surfactant to produce water emulsified fuels [38]; biodiesel, jet fuel and diesel in water were tested in a single cylinder direct injection diesel engine. The authors reported that the engine output power was decreased with the addition of water content in the fuel. The specific fuel consumption (SFC) and thermal efficiency of emulsions were higher than the reference fuel [38]. Elsanusi et. al. [39] investigated the emissions and performance characteristics of a direct injection diesel engine running with biodiesel-diesel-water emulsions. Increase in brake thermal efficiency (BTE) by up to 6% and reduction in NOx and smoke by up to 30% were reported; however, the authors reported that the CO emission was increased substantially with increased water content in the emulsion [39]. Stable emulsion was prepared using 15% water, 75% nerium oleander biofuel, 5% ethanol and 5% surfactant (Span 80), in addition 30 ppm cerium oxide nanoparticle was dispersed in the emulsion to improve the engine performance and emission characteristics [40]. Maximum reduction in NO_x, HC, smoke and CO emission were observed with nano-emulsion fuel when compared with neat nerium oleander biofuel and fossil diesel operation [40]. However, the authors reported that the thermal efficiency and brake specific fuel consumption (BSEC) values of the nano-emulsion fuel were lower than those obtained for fossil diesel [40]. Stable emulsion was made by blending 20% biodiesel, 5% diethyl ether, 10% water, 2% surfactant and 63% pure diesel [41]. The authors reported that emulsified fuel gave 5.7% decrease in SFC, 19% increase in brake efficiency, 12.5% reduction in NO emission, 29% reduction in smoke emission and significant reductions in CO emission when compared to standard fossil diesel. The HC and CO_2 emission were increased when emulsified fuel was used instead of fossil diesel [41].

Very few studies were found in the literature investigating the effects of neat oil emulsions on the engine performance and emissions. Shahronu et al. [42] demonstrated soybean oil – water emulsions without surfactant in a mixing chamber before injection, the emulsified fuel was used in a combustion furnace. They reported that both NOx and soot level were decreased, and sauter mean diameter (SMD) of sprays were increased [42]. Crookes et al. [18] found that rapeseed oil emulsified with 10% water gave a similar thermal efficiency when compared to fossil diesel fuel at various engine loads and speeds; however, these authors also reported that the ignition delay had decreased due to the addition of water [18]. Use of neat oil-fossil diesel blends in the compression ignition (CI) engines can avoid the need for transesterification and associated problems, and are recommended as potential alternative fuels by the researchers due to the associated life cycle energy and emission advantages [15] [43] [44]. However, literature survey shows that there is a clear knowledge gap on how neat oil-fossil diesel emulsion affects engine performance and exhaust emission characteristics. Furthermore, most studies found in literature used direct injection (DI) single cylinder CI engines. However, indirect injection (IDI) engines are likely to receive renewed interests for use with alternative fuels. Due to the partial burning in the pre-chamber, the air-fuel mixing and combustion will be better in the main combustion chamber of the IDI engine than DI engine [45]. Furthermore, IDI engine may emit lower NOx emission as the combustion temperature in the main combustion chamber of the IDI engine will be lower than in the DI engine [45]. The overall aim of the study is to prepare stable neat oil - fossil diesel emulsions to improve performance and emissions in IDI compression ignition engines. Stable (single phase) biofuel - fossil diesel - water emulsions will be prepared using combination of surfactants. A two cylinder indirect injection engine will be used in the study to assess the impact on engine performance and exhaust emissions characteristics. The objectives of this current study are: (i) preparation of single phase stable water - neat rapeseed oil - fossil diesel emulsions using a combination of surfactants, (ii) measurement of physical and chemical properties of the emulsions and comparison of properties with the fossil diesel and neat rapeseed oil, (iii) preparation of the engine test rig and engine testing using the emulsified blended fuels, (iv) measurement and analysis of engine performance and exhaust gas emissions when operated with emulsions, and comparing them with standard fossil diesel and neat rapeseed oil operation.

2. Materials and Methods

2.1 Preparation of emulsified fuels and characterisation

Stable emulsions of water - rapeseed oil - fossil diesel, water - fossil diesel, and water - rapeseed oil were prepared using surfactants. Fossil diesel to EN590 was collected from a local service station and rapeseed oil was bought from a local supermarket. Surfactants and distilled water were collected from Sigma Aldrich and Fischer Scientific Ltd. Hydrophilic-Lipophilic-Balance (HLB) is a ranking used to identify the relative hydrophilicity of the surfactants. The higher the HLB value the higher is the hydrophilic characteristics and the lower the HLB value the higher is the hydrophobic (lipophilic) characteristic. Higher HLB value surfactants are more water soluble; on the other hand, lower HLB value surfactants are more oil soluble. Mixtures of surfactants are generally used to get the optimum HLB value for water-oil emulsions [46]. Surfactants stabilise the surface tension of oil and water during emulsification. Two surfactants, Span 80 and Tween 80, were used in this study to obtain the optimum HLB value for water in rapeseed oil - fossil diesel (biofuel blend) emulsions. The combined HLB values were calculated by using the following relation:

$$HLB_{comb} = (HLB_S \times W_S) + (HLB_T \times W_T)$$

Where, S and T stands for Span 80 and Tween 80 respectively; W is the volume ratio of each surfactant ($W_S + W_T = 1$). HLB_S and HLB_T are the HLB values of Span 80 and Tween 80 respectively. Emulsions of water in biofuel blends (containing 2.5% and 5% water) were prepared using HLB_{comb} values varying from 5 to 8. The emulsions were kept at room temperature for 15 days and examined for changes in stability before and after. The trial showed that a combined HLB value of 5 was relatively the most suitable surfactants composition for water in rapeseed oil-diesel (water in biofuel blends), and also, separately, with rapeseed oil and fossil diesel emulsions. A combination of 10% (vol.) Tween and 90% (vol.) Span were used to achieve the optimum HLB value. No phase separation was observed after 15 days (Fig. 1). All emulsions were made using the same procedure at room temperature of about 19 °C. At first, the blend of fossil diesel and rapeseed oil was prepared in a sample bottle. Then the required amount of Span 80 was added in the biofuel - diesel blend. The whole mixture was then stirred for about 120 seconds. After that, distilled water and Tween 80 was mixed at appropriate ratios in a separate bottle. The mixture was stirred and then poured into the biofuel blend - Span mixture. The whole mixture was then stirred and shook for about 120 seconds. Four stable emulsions were prepared - (i) E1: 95.5% rapeseed oil + 2.5% distilled water + 2%

surfactant (10% Tween 80 + 90% Span 80), (ii) E2: 95.5% fossil diesel + 2.5% distilled water + 2% surfactant (10% Tween 80 + 90% Span 80), (iii) E3: 80.5% fossil diesel + 15% rapeseed oil + 2.5% distilled water + 2% surfactant (10% Tween 80 + 90% Span 80), and (iv) E4: 78% fossil diesel + 15% rapeseed oil + 5% distilled water + 2% surfactant (10% Tween 80 + 90% Span 80). Various properties of the fuels and emulsions were measured and then compared with the respective properties of the neat fossil diesel and neat rape seed oil. The heating value was measured using the Parr 6100 Bomb Calorimeter in accordance with ASTM-D240 standard. The flash point temperature was measured using the Setaflash closed cup flash point tester (model 33000-0) in accordance with ASTM-D3278 standard. The kinematic viscosity at various temperatures were measured as per ASTM-D130 standard, using the Cannon Fenski u-tube viscosity meter and a thermostatic water bath. The density of the fuel samples were measured using the hydrometer in accordance with measurement standard ASTM-D4052. Multiple readings were taken for each measurement to ensure reputability of the results.

2.2 Engine Testing

A two cylinder Lister Peter indirect injection compression ignition engine was used (Table 1), the engine was connected to a Heenan and Froude (model: DPX1) water-brake dynamometer to apply load on the engine. The fuel supply system to the engine was modified, figure 2 shows schematic diagram of the engine test rig system. Two fuel tanks were used – one for neat fossil diesel and the other for test (or switching) fuels. An extra in-line 12v fuel pump was used to aid the fuel flow into the engine. The tests were carried out at a constant speed of 2000 rpm. The engine was first started with neat fossil diesel and operated for about 20 minutes, switched to neat rapeseed oil operation and then finally switched to emulsified fuel operation. After each test, the engine was switched back to fossil diesel operation and operated for about 20 minutes before stopping the engine. For maintaining the accuracy of measurements, extra care were taken to avoid mixing of the fuel samples in the fuel supply system and in fuel tanks. The fuel tanks were cleaned and dried using the acetone before putting a new test fuel in the tank. The loads on the engine were varied from minimum to maximum, the speed was kept constant. Fuel consumption at each load was measured manually using a glass cylinder and a stop watch. Bosch RTM 430 smoke meter and Bosch BEA 850 emission analyser were used to measure the smoke intensity and composition of gases in the exhaust stream (Fig. 2). Exhaust gas temperature was measured at the exhaust pipe surface using a k-type thermocouple and a portable thermocouple reader. For each load, multiple readings were taken until repeatability of the measurements were ensured. In order to flush out the old fuel from the engine no measurements were taken in the first 15 minutes of engine operation on the test fuel. The engine was operated with each test fuel for about two hours allowing roughly 20 minutes at each engine load. Engine performance and exhaust gas emissions characteristics of emulsified fuels operation were compared with the corresponding characteristics of neat fossil diesel and neat rape seed oil operation.

3. Results and Discussion

3.1 Fuels Characterisation

Figures 3 to 6 shows various properties of the emulsified fuels and how they differ with respect to the corresponding properties of the neat fossil diesel (FD100) and neat rapeseed oil (RO100). Due to the water content, the emulsified fuels gave lower calorific values when compared to neat rapeseed or fossil diesel fuels (Fig. 3). However, the results showed that for the same water content, the rate of decrease in heating values were higher in the case fossil diesel emulsions than biofuel emulsions. Out of the four emulsions, the heating value of emulsion E2 was decreased by 3.3% when compared to the heating value of 100 FD. On the other hand, for same water content, the heating value of rape seed oil emulsion (E1) was decreased by about 2.5% when compared to the corresponding value of the neat rape seed oil. The heating value of the biofuel blend emulsion (E3) was 16.8% higher than RO 100 and 6.7% lower than FD 100 fuels. For the same engine power output, fuels with lower heating values (than diesel) would lead to higher brake specific fuel consumption than for fossil diesel operation. The density of the emulsions were increased by a small amount due to the higher density of the water (and surfactants) than fuels (Fig. 4). For example, the density of RO emulsion (E1) was approximately 1% higher than RO 100 fuel. The density of the biofuel blend emulsion (E3) was 2.4% higher than the corresponding density of the neat FD (Fig. 4). However, on the other hand, the density of the E3 emulsion was about 7% lower than that of RO 100 fuel (Fig. 4). Density of the fuel affects ignition delay and fuel injection parameters; the higher the density higher would be the ignition delay. Fuels with high density and low heating values can compensate engine power. On the other hand, use of high density fuels can emit high NOx emissions. The flash point temperatures are important for storing and transportation of the fuels. Fuels with high flash point temperatures are used in the compression ignition engine. In general, the flash point temperatures of the emulsions were higher than that of neat fossil diesel. The flash point of RO emulsion (E1) was about 5% higher than the corresponding flash point temperature of the neat RO (Fig. 5). Interestingly, the flash point temperature of the biofuel blend emulsion (E3) was increased by 15.4% and decreased by 36% when compared to neat FD and neat RO fuels respectively. The viscosities of the fuels affects injection parameters (sauter mean diameter, spray angle, spray penetration length) and hence combustion characteristics; the viscosities change with temperature. The poor atomisation quality of the high viscosity fuel might lead to higher CO and smoke emissions. In addition, use of high viscosity fuels could clog filters, fuel supply systems and injector holes. Figure 6 shows kinematic viscosities of the fuel samples at various temperatures. It was observed that the viscosities of the all fuels decreased with the increase of temperatures. The viscosities of the neat RO fuel was much higher than the viscosities of emulsions; however, at 40^{o}C, the viscosities of emulsions (except E1) were comparable to that of neat FD value. Interestingly, at 40^{o}C, the viscosity of the emulsion E2 was approximately 2% lower than the corresponding value of fossil diesel (Fig. 6).

3.2 Performance Characteristics

Three emulsions containing the same water content (ie. 2.5%) were tested in the engine and compared against the engine performance and emissions characteristics with pure fossil diesel and pure rapeseed oil operation. It was found that the full engine power was achieved when emulsified fuels were used instead of neat fossil diesel. However, at higher engine loads, an extra in-line fuel pump was used in the case of emulsified fuel operation in order to aid the smooth flow of fuel to the engine. Due to higher oxygen content and suspended water particles, emulsified fuels (except E3) gave higher thermal efficiency than neat fossil diesel operation (Fig. 7). Similar results were reported in the literature for other types of emulsified fuels [20, 37]. At full load, the thermal efficiency of E1 emulsion was approximately 12% higher than that of fossil diesel (Fig. 7). However, in almost all engine loads and for all fuels, 100 RO gave highest thermal efficiency. It was believed that the combined effects of the higher oxygen content, indirect injection and higher calorific values (compared to emulsions) of RO100 fuel produced this behaviour. On the other hand, amongst all emulsions, E3 had lowest oxygen content and gave lowest thermal efficiency. At full load, the efficiency of E3 emulsion was about 4% lower than that of fossil diesel. The bsfc of the emulsified biofuel blend and RO100 fuels were higher than the corresponding values obtained for FD 100 fuel (Fig. 8a). In general, the bsfc of the biofuel emulsions were higher; higher viscosity and lower calorific values caused this characteristics. Higher bsfc values found in this study resemble to the results found in the literature for other emulsified fuels [38]. Interestingly, at higher loads, the bsfc of the biofuel blend emulsion (E3) was very close to the fossil diesel value, it was thought that better combustion characteristics due to both indirect injection and exploded combustion (caused due to micro emulsions) caused this. Furthermore, in all engine loads, the BSFC values of both FD100 and FD emulsion (E2) were very close to each other (Fig. 8a). Similar characteristic was also observed for RO 100 and RO emulsion (E1). However, amongst all fuels, the brake specific energy consumption (bsec) of both 100 RO and emulsion E1 fuels were lowest (Fig. 8b). In almost all engine load, the bsec of the 100 FD and biofuel blend emulsion (E3) were very close to each other. At full load, the bsec of the 100 FD was about 9% higher than emulsion E1 (Fig. 8b). Better combustion due to micro emulsions of the water molecules caused this.

3.3 Exhaust Emission

For all fuels, the higher the engine load the higher was the CO_2 emissions. Compared FD 100, the emulsified fuels gave slightly higher CO_2 emissions (Fig. 9). Similar results was also found in the literature [41]. Higher bsfc values and higher oxygen content in the emulsified fuels caused higher CO_2 emissions. The CO_2 emissions of FD 100 and biofuel blend emulsion (E3) were almost similar. For example, at full load, biofuel blend (E3) CO_2 emission was about 1% higher than the corresponding FD 100 value. Emulsion E1 gave highest CO_2 emission due to highest bsfc value (Figs 8 and 9). No specific trend was found for CO emissions; in most cases, FD 100 and FD emulsion E2 gave lower CO gas emissions (Fig. 10). Furthermore, at medium engine loads, it was observed that emulsified fuels E1 and E3 gave similar CO emissions when compared to the corresponding values of FD100 fuel (Fig. 10). On the other hand, at low engine loads, emulsions gave higher CO gas emissions than FD 100. It was thought that the lower combustion temperature at low loads could not break down the suspended water molecules efficiently and hence led to higher CO emissions. Higher CO emission observed in this study is in-line with the results found in the literature for fossil diesel-water emulsion fuels [29, 33]. At full load, the CO emission of the RO 100 and RO emulsion (E1) were higher than those of other fuels (Fig. 10). Combined effects of higher values of viscosity and oxygen content of these two fuels might have caused this.

All emulsified fuels and RO 100 fuel produced lower NOx gas emissions than neat fossil diesel operation (Fig. 11). At full engine load, the NOx emissions of E1 and E3 emulsions were about 15% and 12% lower than the corresponding NOx emissions of FD 100 fuel (Fig. 11). Similar results were also observed by other researchers in the case of emulsified fuels [32, 34, 42]. Due to the addition of water in the fuel, the combustion temperature of the emulsified fuels were expected to be lower than FD 100 and RO 100 fuels. Lower combustion temperature then led to lower NOx gas emissions. At higher loads, the combustion temperature was higher, the combined effects of higher combustion temperature and indirect injection might have caused higher NOx emissions in the case of FD emulsion (E2). However, at full load condition, the NOx gas emission values of emulsion E1 and E3 were very close to each other (Fig. 11). At low to medium engine loads, emulsified fuels gave slightly higher O_2 emission than neat fossil diesel (Fig. 12). At full load, they tend to emit slightly lower O_2 emission than those of FD 100 fuel. Poor combustion characteristics of emulsified fuels at low loads could be the reason for this behaviour. Interestingly, in almost all loads, the smoke intensity of the emulsified fuels and RO 100 fuel were lower than the FD 100 operation (Fig. 13). At 100% load, the smoke intensity of biofuel blend emulsion (E3) was 29% lower than the corresponding value of FD 100 fuel (Fig. 13). The lowest smoke was observed for E1; at full load, E1 gave 46% lower smoke than that of fossil diesel (Fig. 13). Better combustion characteristics of emulsified fuels gave lower smoke than diesel. In general, the exhaust gas temperatures were decreased by about 20% when emulsified fuels were used in the engine instead of neat fossil diesel (Fig. 14). However, at full load, due to higher bsfc, the exhaust gas temperatures of the emulsified fuels were similar to those of neat fossil diesel values (Fig. 14).

4. Conclusion and recommendation

Stable single phase biofuel and biofuel-fossil diesel blend emulsions were made. Properties of the biofuel emulsions were measured and compared them with the neat fossil diesel and neat biofuel properties. The biofuel blend emulsion, biofuel emulsion and fossil diesel emulsion were tested successfully in a multi-cylinder indirect injection compression ignition engine. The main findings of the study are summarised below:

01. Biofuel and biofuel-diesel blend emulsions were prepared using an optimised HLB value of the blended surfactants (Tween and Span). The emulsions were stable and no phase separation was noticed.

02. Due to water addition, the heating values of the emulsions were lower than the corresponding neat fossil diesel and neat biofuel values. The heating value of the biofuel-diesel blend emulsion (E3) was 16.8% higher than RO 100 and 6.7% lower than FD 100 fuels. The density of the emulsions were slightly higher than those obtained for neat fuels. The density of the biofuel-diesel blend emulsion was about 7% lower than that of neat biofuel. The flash point temperature of the biofuel emulsion was increased by 5% when compared to neat biofuel. The biofuel-diesel blend flash point temperature was 15.4% higher than the corresponding fossil diesel value. At 40^{o}C, the kinematic viscosities of the most emulsions were almost similar to that of neat fossil diesel value.

03. All emulsions gave full engine power. Due to better combustion, emulsified fuels gave higher thermal efficiency than fossil diesel. The efficiency of the biofuel emulsion was approximately 12% higher than that of fossil diesel at full engine load operation. At full load operation, bsfc of the biofuel-diesel blend emulsion was approximately 3% higher than that of fossil diesel. Both FD 100 and FD emulsions gave similar bsfc values. The bsec values of the neat fossil diesel and biofuel-diesel blend emulsion were very close to each other.

04. Regarding exhaust emissions, it was observed that the emulsion fuels produced up to 15% lower NOx emissions than fossil diesel. Latent heat of evaporation of water molecules caused NOx reduction characteristics. At full load, the CO_2 emission of biofuel-diesel blend emulsion was about 1% higher than the corresponding FD 100 value. Due to the microexplosion and higher evaporation rate, biofuel emulsions produced less smoke; at full load condition, biofuel-diesel blend emulsion gave 29% lower smoke than the corresponding FD 100 value. The exhaust gas temperatures were found to be lower in the case of emulsified fuels than fossil diesel fuel. Due to higher bsfc values of the emulsified fuels at higher loads, the exhaust gas temperatures were almost same for all fuels.

The current study proved that neat oil-fossil diesel blend emulsion can be used directly in an unmodified indirect injection compression ignition engine. The emulsions gave thermal efficiency and emissions advantages as compared to neat fossil diesel or neat biofuel operation. More studies using other types of neat oil (using edible and non-edible oils) biofuel-diesel blends and other engine configuration are recommended. Use of other surfactants and higher water content in the emulsions are other areas for further investigation.

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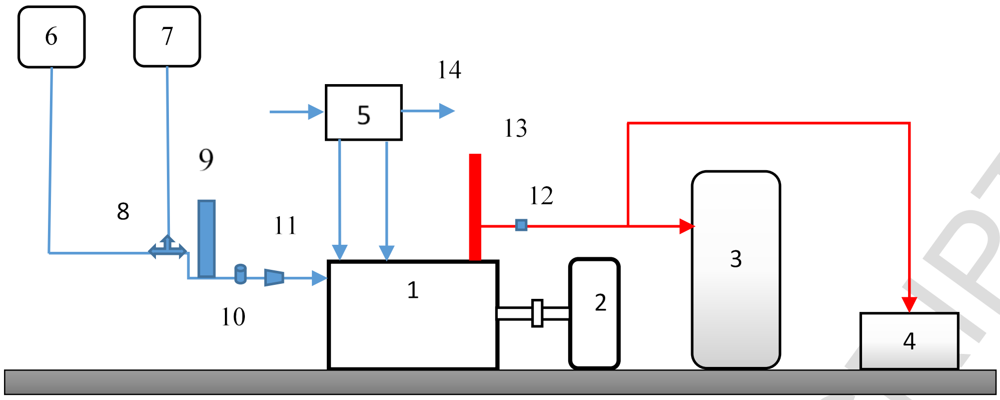
Figure 1 - Fuel samples (from left to right): fossil diesel, emulsion E1, emulsion E2 and emulsion E3



1: Engine, 2: Brake Dynamometer, 3: Exhaust Analyser, 4: Smoke Meter, 5: Engine Cooling System Heat Exchanger, 6: Fossil Diesel Tank, 7: Emulsified Fuel Tank, 8: Three-way Valve, 9: Fuel Consumption Measurement, 10: Fuel Filter, 11: In-line Fuel Pump, 12: Exhaust Thermocouple, 13: Main Exhaust, 14: Test Cell Cooling System

Figure 2 - Indirect injection multi-cylinder engine test rig and various measurements

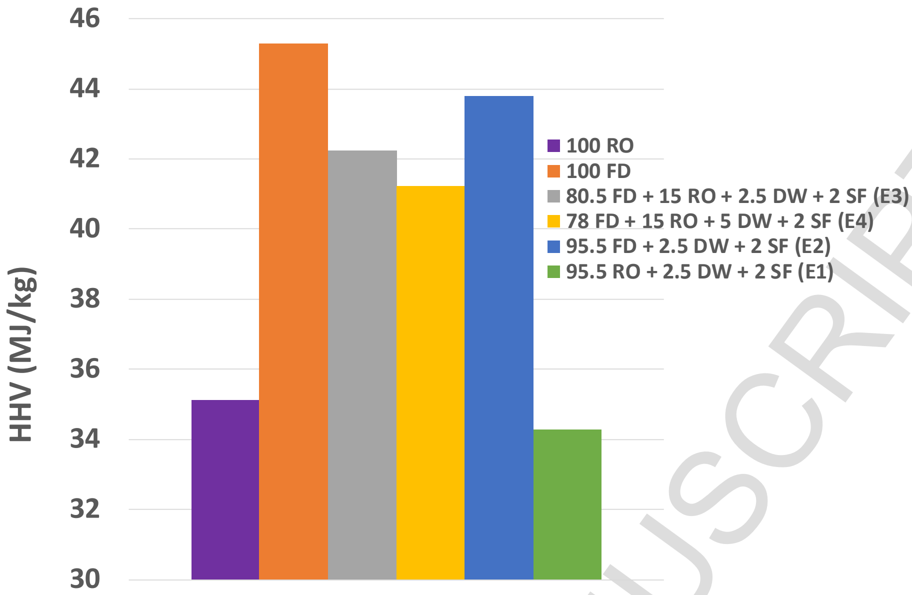


Figure 3 - Higher Heating values (MJ/kg) of the emulsified fuels, diesel and rapeseed oil

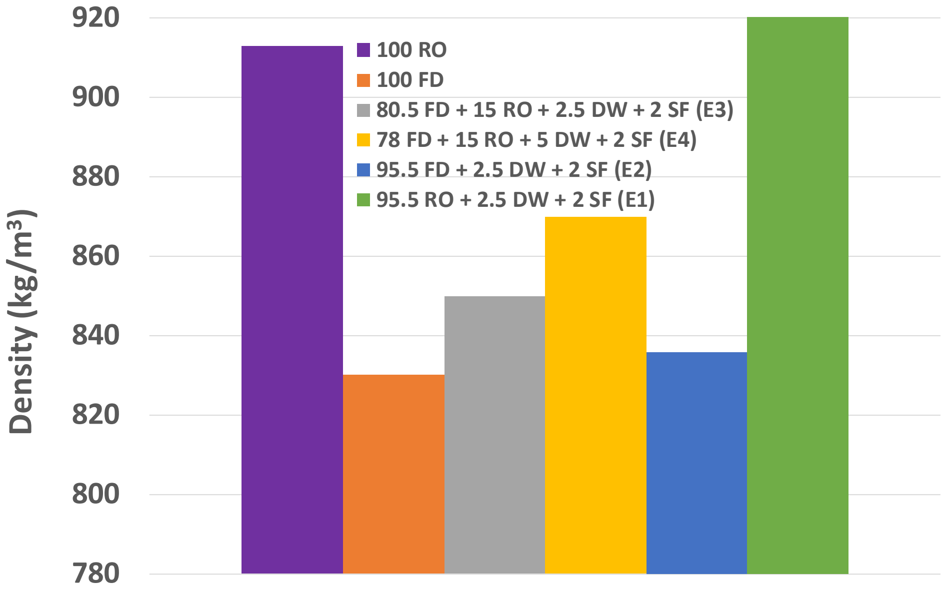


Figure 4 - Density (kg/m^3) of the emulsified fuels, fossil diesel and rapeseed oil

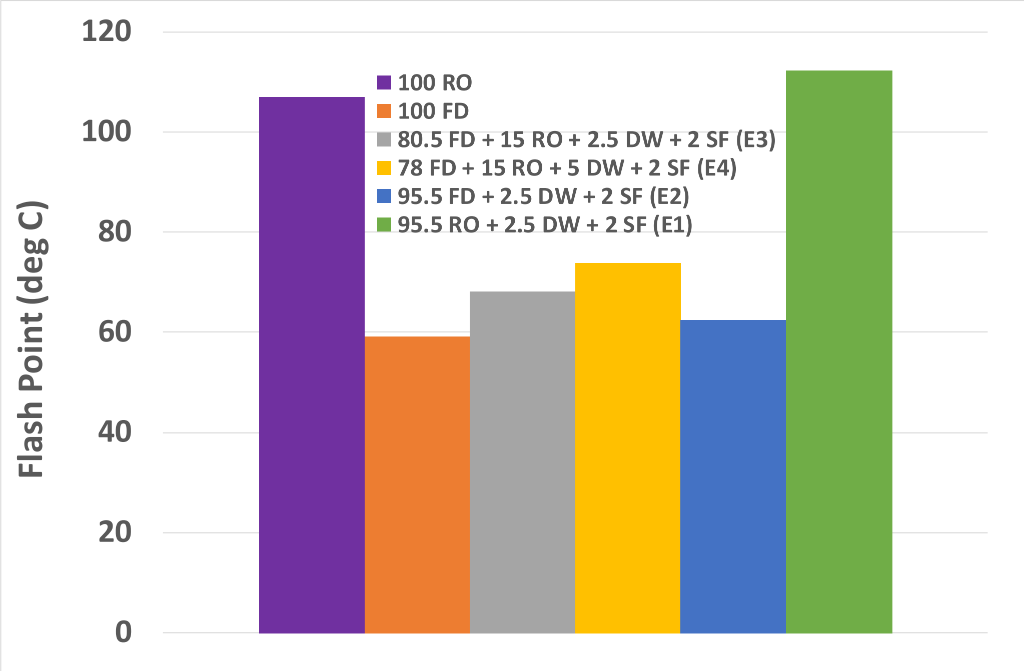


Figure 5 - Flash point temperature (^{0}C) of the emulsified fuels, fossil diesel and rapeseed oil

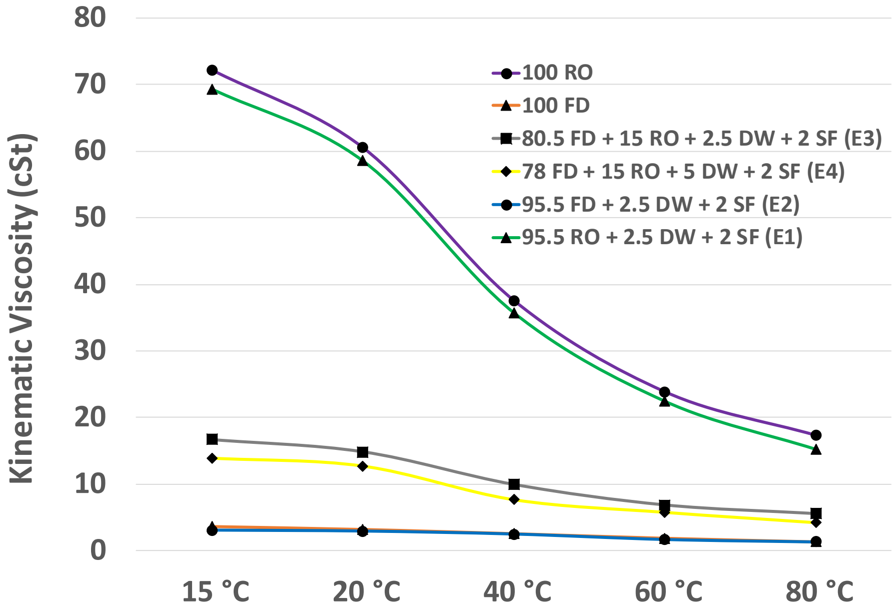


Figure 6 - Kinematic viscosity (cSt) of the emulsified fuels, fossil diesel and rapeseed oil as a function of temperature

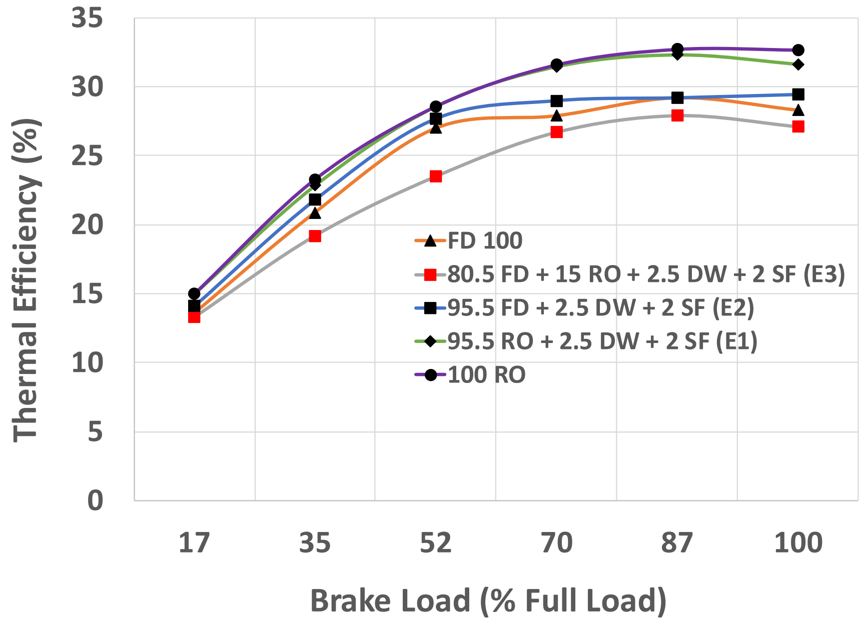


Figure 7 - Thermal efficiency of the emulsified fuels, fossil diesel and rapeseed oil

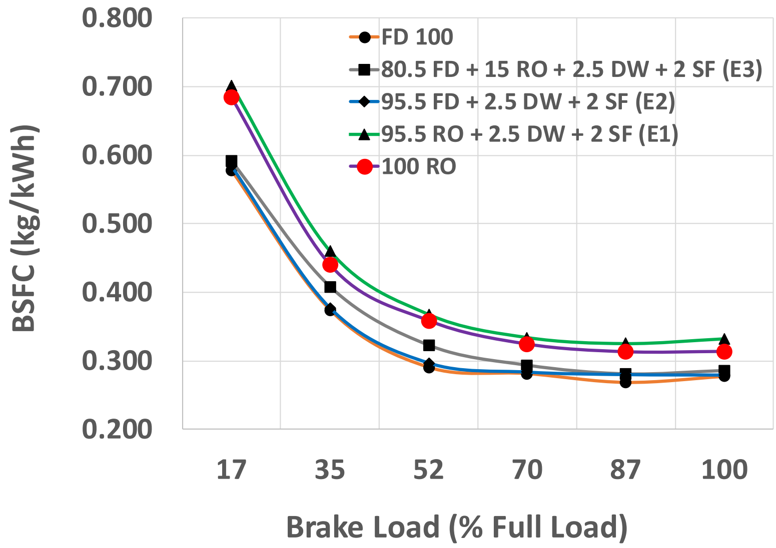


Figure 8a – BSFC vs. engine load

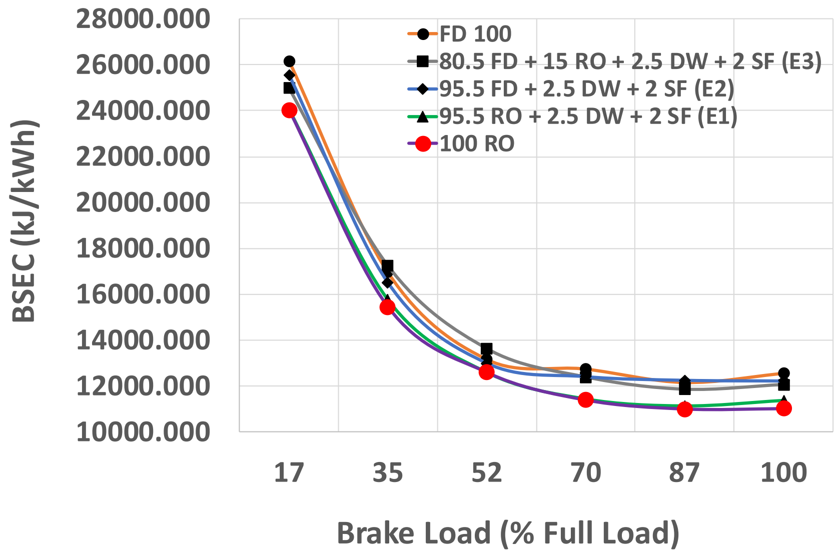


Figure 8b – BSEC vs. engine load

Figure 8 - (a) Brake specific fuel consumption (bsfc) and (b) brake specific energy consumption (bsec) of the emulsified fuels, fossil diesel and rapeseed oil

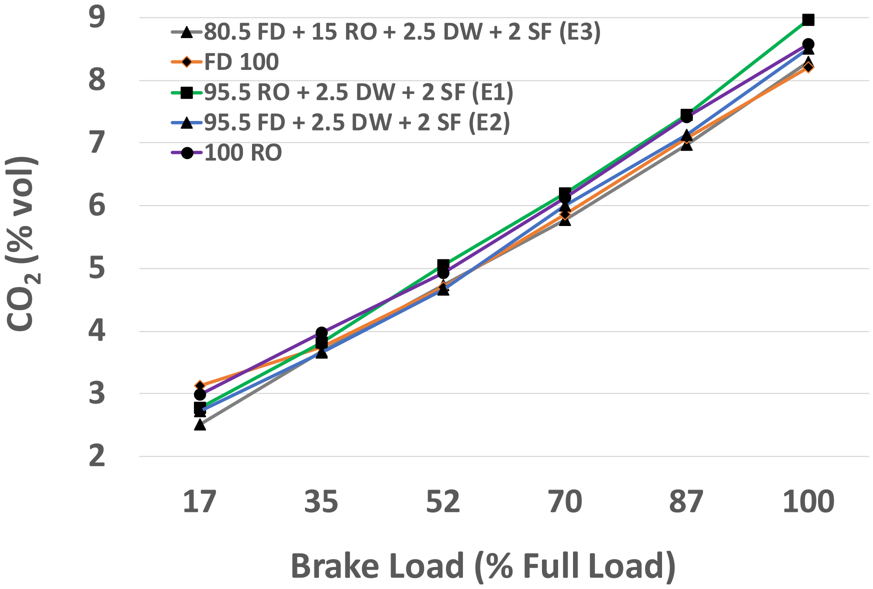


Figure 9 - CO_2 emissions of the emulsified fuels, fossil diesel and rapeseed oil

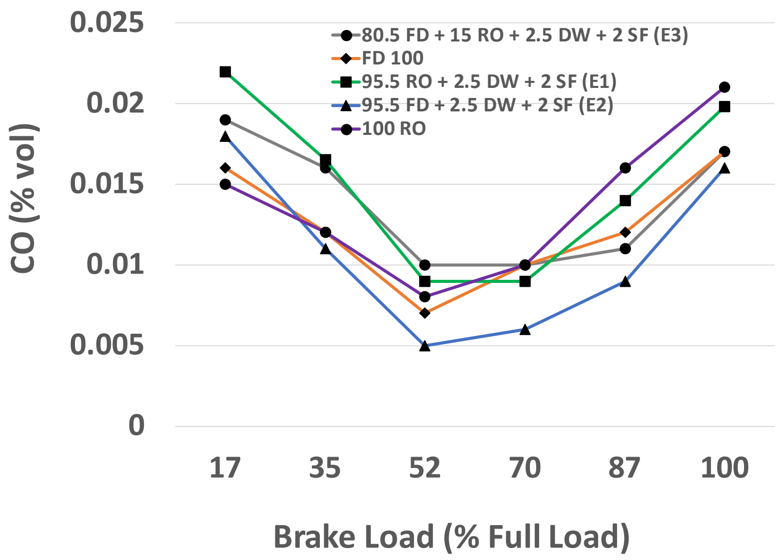


Figure 10 - CO emissions of the emulsified fuels, fossil diesel and rapeseed oil

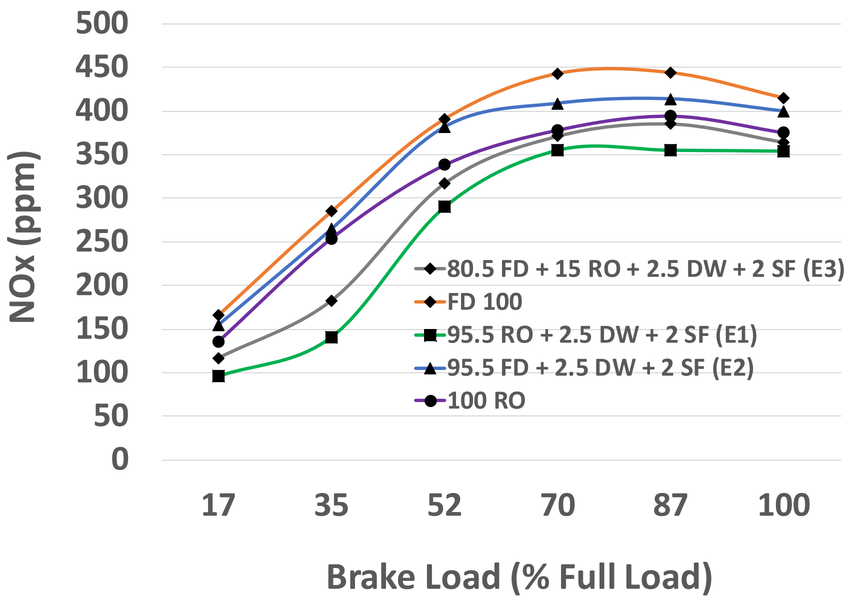


Figure 11 - NOx emission values of the emulsified fuels, fossil diesel and rapeseed oil

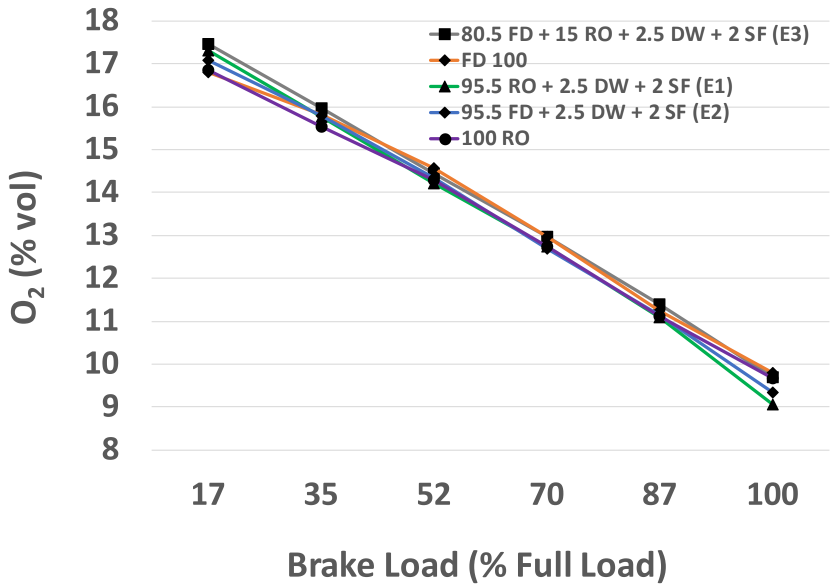


Figure 12 - O_2 emissions of the emulsified fuels, fossil diesel and rapeseed oil

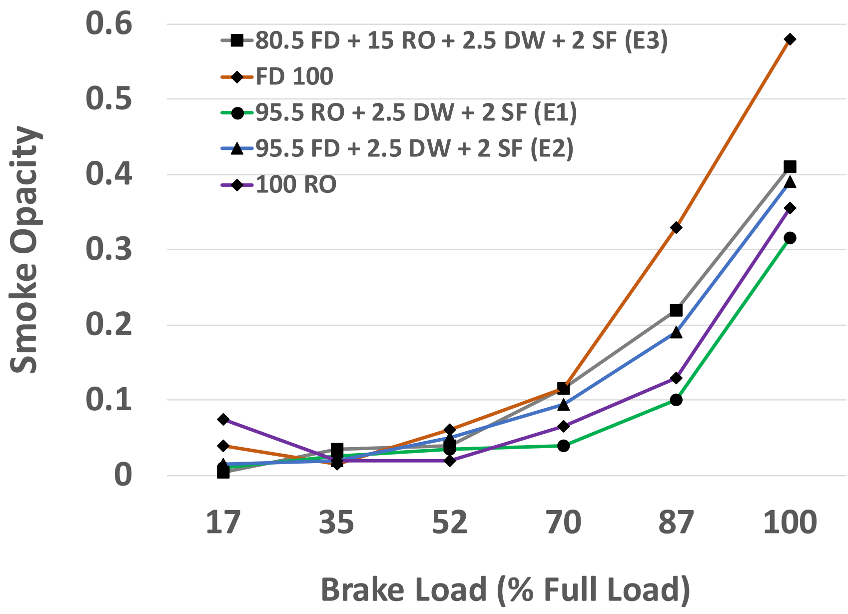


Figure 13 - Smoke opacity values of the emulsified fuels, fossil diesel and rapeseed oil

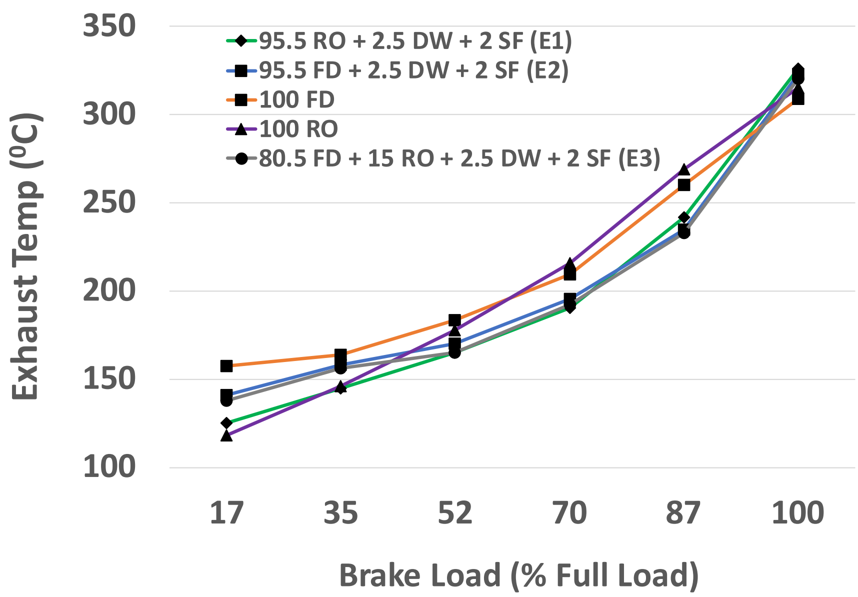


Figure 14 – Exhaust gas temperature of the emulsified fuels, diesel and rapeseed oil

HIGHLIGHTS

- Stable single phase biofuel-diesel blend emulsions were prepared
- Thermal efficiency of the emulsion was increased by up to 12% than for diesel
- At high loads, bsfc of the biofuel blend emulsion was very close to that of diesel
- Biofuel emulsion operation gave up to 15% NOx gas reduction than diesel
- Smoke intensity of the emulsion was about 29% lower than diesel operation

Table 1: Specification of the 2-cylinder indirect injection engine

Manufacturer	Lister Petter
Model	LPWS2
Fuel	Diesel
Injection type	Indirect
No. of cylinders	2
No. of strokes	4
Rated power	7.4 kW at 2000 rpm
Continuous power	14 kW at 3500 rpm
Bore	86.0 mm
Cylinder capacity	0.930 litre
Stroke	80 mm
Compression ratio	22:1