Renewable Energy 96 (2016) 433–441

Contents lists available at ScienceDirect

Renewable Energy

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

# Optimisation of Karanja/Jatropha-Methanol emulsification variables and their engine evaluation

Avinash Kumar Agarwal [a, *], Vikas Katiyar [b], Kushagra Singh [a]

[a] Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur, 208016, India
[b] Environmental Engineering and Management Program, Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur, 208016, India

ARTICLE INFO

*Article history:*
Received 6 July 2015
Received in revised form
14 March 2016
Accepted 29 April 2016

*Keywords:*
Emulsified fuels
Performance
Emissions
Methanol
Jatropha
Karanja

ABSTRACT

Vegetable oil based emulsified fuels have emerged as an attractive option for existing diesel engines. The issues such as higher viscosity and exhaust emissions such as oxides of nitrogen ($NO_X$), particulate matter (PM) are associated with straight vegetables oils (SVO), which can be potentially eliminated by making SVO emulsions, without worrying about PM-$NO_X$ trade-off. In this study, emulsions were prepared, where methanol was used as a dispersed phase and SVOs (Jatropha and Karanja) were used as continuous phase. A non-ionic commercial surfactant 'Sorbitan monooleate' also known as 'Span®80' was added and the mixture was stirred by a mechanical stirrer to produce emulsified fuel. Effect of several process variables such as surfactant concentration, stirrer speed and stirring duration on emulsion stability were optimised. The optimum surfactant concentration, stirrer speed, and stirring duration were determined for Methanol-Jatropha/Karanja emulsions. Emulsified fuels had important fuel properties comparable to baseline mineral diesel. These emulsions were blended with diesel in 1:3 proportions and evaluated in a single cylinder diesel engine for their performance and emissions characteristics. Performance and emission characteristics of emulsified blends followed a trend, which was related to methanol concentration in the dispersed phase of the emulsions.



## 1. Introduction

Worldwide there is an increasing concern over combustion-generated pollutants such as particulate matter (PM), oxides of nitrogen ($NO_x$), carbon monoxide (CO) and total hydrocarbons (THC). This has forced the regulatory agencies worldwide to implement stringent emission regulations in different parts of the world to tackle the pollution at source. Diesel engines are widely used because of their high thermal efficiency, reliability, adaptability and cost effectiveness in long-term. However, they are one of the main source of pollutants such as PM and $NO_x$ in the environment. It is difficult to comply with stringent emission norms for PM and $NO_x$ only by improving combustion chamber design and injection systems. It is accepted widely that clean combustion in diesel engines can be achieved by engine improvements, in addition to fuel reformulation.

Oil crisis in 1970 had forced many countries to explore using alternate fuels as a partial replacement of fossil fuels [1]. These alternate fuels should be renewable, sustainable, efficient, cost-effective and locally available in order to be commercially viable, environment friendly and acceptable. Biofuels, such as ethanol/methanol, straight vegetable oils (SVO) and biodiesel are gaining prominence from energy security and environmental preservation point of view because these fuels can provide large-scale employment in rural areas of developing countries since their processing can be done in rural areas itself, without the need for transporting them long distance. This therefore eliminates transportation cost for distribution [2]. In addition, large dependence of developing economies on imported fuel leads to significant economic stress on their foreign exchange reserves [3]. According to an estimate, India alone imported ~189 MMT crude oil during FY 2013–2014, valued at US$ 140 billion, which caused a huge burden on the exchequer [4]. Demand for crude oil is continuously rising every year. Each 1 US$ increase in crude oil price increases India's petroleum import bill by ~620 million US$/year [5]. In such a scenario, diesel fuel production from locally available resources is an attractive option in developing countries to fulfill demand for transportation fuels in future. Using vegetable oils and their derivatives is an effective option for reducing burden on imported petroleum fuels. India has

* Corresponding author.
*E-mail address:* akag@iitk.ac.in (A.K. Agarwal).

http://dx.doi.org/10.1016/j.renene.2016.04.092
0960-1481/

more than 300 different varieties of vegetable oils available in surplus quantities, which can be potentially used as alternate fuels. Jatropha and Karanja are two main species, which are available in huge surplus quantities throughout south Asia.

The use of emulsified fuels with vegetable oils or its derivatives as base fuel is being increasingly considered as alternative to diesel worldwide. Vegetable oils of different kinds can be produced domestically either from a large variety of trees or from crops, which can be grown in marginal or fallow lands. Several researchers are trying to resolve the issue of high peak combustion temperature in the cylinder without affecting engine performance for reducing $NO_X$ emissions however in-cylinder methods adopted to reduce $NO_X$ increase PM emissions. Moreover when such methods are used, they increase operating cost as well as maintenance cost. Therefore more effective methods are required to reduce $NO_x$ emissions. Use of emulsified fuels is one such method, which can resolve this problem in long-term and increase the fuel efficiency by reducing emission of hazardous pollutants such as PM and $NO_x$ simultaneously from diesel engines [6,7]. Emulsified fuel technology is one of the alternatives, which will dominate diesel locomotives and automotive sectors [6]. These SVO derivative fuels offer advantages such as they are renewable and biodegradable, emit lower exhaust gas emissions, and contribute to reduction in GHG emissions such as $CO_2$ [8].

Vegetable oils can also be used as alternate fuel directly in diesel engines because they have comparable cetane numbers and calorific value as that of baseline mineral diesel. However, their brake thermal efficiency (BTE) is inferior compared to diesel and they emit high smoke, HC and CO emissions. These artifacts are observed because of their relatively higher viscosity and lower volatility compared to baseline mineral diesel, which creates fuel atomization issues and inferior fuel-air mixing [9]. In previous experimental studies, other than fuel preheating [10], two other solutions emerged while using SVOs as diesel engine fuel. These are (i) transesterification and (ii) emulsification of SVOs. Transesterification and emulsification technologies were adopted to improve spray characteristics that were undermined by high viscosity of vegetable oils [11]. Transesterification produces biodiesel and emulsification produces emulsions. Both these fuels exhibit improved combustion and reduced pollutant emissions from diesel engines [6,12]. Transesterification is a relatively expensive technique of fuel processing due to specific materials and processing requirements. On the other hand, emulsification requires only a mechanical stirrer and surface active agents, which are called surfactants or emulsifiers [13]. Methanol is a primary alcohol, which is also produced from biomass resources and is available in huge surplus quantities world-over. Previous studies on use of methanol/animal fat emulsions revealed that use of methanol for emulsification reduces viscosity and increases stability of animal fat emulsions. It has been reported that methanol/animal fat emulsions significantly reduce emissions from a CI engine [14,15]. From a comprehensive review of literature, it can be concluded that there are some issues related to emulsion preparation, namely types of surfactants used and their hydrophilic lipophilic balance (HLB), the method used to preparing emulsions, their category and characteristics. Surfactants are essential to modify the unbalanced forces on the surfaces of fluids, thereby modifying the surface tension [7]. Abu [16] performed experiments in a single-cylinder water-cooled diesel engine to study the effect of diesel-water emulsions on engine performance and exhaust gas temperature. Emulsified diesel fuels with 0, 5, 10, 15, and 20% water/diesel ratios (v/v) were used at an engine speed ranging from 1200 to 3300 rpm. Results indicated that addition of water in emulsion improved combustion efficiency. The engine torque, power, and brake thermal efficiency increased with increasing water content in emulsion [16]. Biodiesel is denser and less compressible than diesel and its longer chain length and saturation level increases its density, speed of sound and isentropic bulk modulus compared to mineral diesel. Many researchers have reported that biodiesel emitted lower emissions such as 20% lower carbon monoxide (CO), 30% lower hydrocarbons (HC) and 50% lower soot emissions compared to baseline mineral diesel. However, biodiesel also emitted 10–15% higher $NO_x$ emissions [16]. Although previous studies using emulsified diesel have reported lower smoke, PM, and $NO_x$ emissions but it also led to reduction in combustion efficiency. Emulsification techniques applied to biofuels have not been studied thoroughly. In view of the above discussion, the objective of present experimental investigation was to determine optimum emulsification parameters for Jatropha and Karanja oils with methanol. In this study, methanol was used as a dispersed phase and vegetable oils (Jatropha and Karanja) were used as continuous phase. Further, these emulsions were blended with mineral diesel and then compared with baseline mineral diesel for their engine performance and emission characteristics.

## 2. Experimental setup and methodology

Emulsification is a possible approach for improving specific fuel consumption and reducing pollutants emitted by CI engines. The potential of using two-phase emulsions as an alternative fuel for engine combustion is worthy of further experimental evaluation. Several surfactants were screened before this study and a non-ionic commercial surfactant 'Sorbitan monooleate' also known as 'Span®80' was found to be the most effective for emulsification of vegetable oils. Emulsions of methanol in Jatropha oil (M/J) and methanol in Karanja oil (M/K) were prepared for these investigations, by adding Span®80 and stirred by a mechanical stirrer. Methanol was used as one of the constituents in preparing the emulsion with an aim of reducing fuel density and viscosity of emulsion, in addition to taking advantage of relatively higher combustion efficiency of oxygenated fuels. The effect of several process variables such as surfactant dosage, stirrer speed and stirring duration on the emulsion stability was studied. Optimization of process variables and stability of emulsion was experimentally evaluated by measuring relative volume of emulsion over one week under ambient storage conditions of the emulsified fuels.

### 2.1. Contents of emulsion

#### 2.1.1. Vegetable oils

Karanja (*Pongamia Glabra*) and Jatropha (*Jatropha Curcas*) oils were used as continuous phase for preparing the emulsion. Triglycerides are the basic constituents of vegetable oils.

#### 2.1.2. Methanol

Methanol was acquired from Qualigens Chemicals Limited, Mumbai, India, and it had impurity of water ~0.2% (v/v) and boiling point of 65.3 °C.

#### 2.1.3. Diesel

Mineral diesel was acquired from local diesel pump. The boiling range of diesel was 180–360 °C.

#### 2.1.4. Surfactant

A commercial surfactant Span®80 (Sorbitan monooleate) was acquired commercially. The emulsifying agent or surfactant forms a thin interfacial film between the two liquids (vegetable oil and methanol in this case) to decrease water surface tension and minimize contact, coalescence, and aggregation of internal dispersed phase [17]. Its chemical structure is shown in Fig. 1.

### 2.2. Emulsion stability and optimization of process variables

In this study, emulsion stability was characterized by the relative volume of emulsion as shown in Fig. 2. Relative volume of emulsion is defined as the ratio of volume of emulsion (LE) to the total volume of methanol, oil and surfactant put together (TE). A higher ratio indicates greater stability of the emulsion [19].

The surfactant concentration was optimized by preparing emulsions (M/J, M/K) using different dosage of surfactant (0.25%, 0.50%, 0.75%, 1.00% and 1.50% v/v) and 15 min of stirring at constant stirrer speed (1500 rpm). The relative volume of emulsion was measured for one week and the dose corresponding to the sample having higher relative volume of emulsion was taken as optimum concentration of surfactant [20]. For this concentration of surfactant and 15 min mixing duration, fresh samples of emulsions were prepared at different stirrer speeds (1200, 1400, 1800, 2200 and 2600 rpm). Relative volumes of these emulsions were measured again for one week. The stirring speed corresponding to highest relative volume of emulsion was considered as optimum stirrer speed. This approach was used to investigate the stability of emulsions for the following samples: (i) 5%, 10% and 15% (v/v) Methanol in Jatropha (M/J); and (ii) 5%, 10% and 15% (v/v) Methanol in Karanja (M/K).

### 2.3. Engine experiment

A four-stroke, single-cylinder, constant-speed, water-cooled, direct-injection diesel engine (Kirloskar; DM-10) was installed with an AC alternator (Kirloskar; 5 KVA) for carrying out engine performance and emissions experiments using emulsified fuels. Fuel injection pressure of the mechanical fuel injection equipment was set at 210 bar, as recommended by the manufacturer. The engine operated at a constant speed of 1500 rpm during the tests. The engine-alternator system was connected to a resistive load bank consisting of heating coils (1000 w each) in order to load the alternator, which in-turn loads the engine. Schematic of the experimental setup for engine investigations is shown in Fig. 3.

Measurements of regulated exhaust gases ($NO_x$, HC, CO, $O_2$ and $CO_2$) was done by exhaust gas emission analyser (AVL; Digas-444) and smoke opacity of the exhaust gas was measured by smoke opacimeter (AVL; 437). The basic principle for measurement of $NO_x$, $CO_2$, CO and HC is non-diffractive infrared radiation (NDIR), and electrochemical method for $O_2$ measurement. Measurement range and resolution of the exhaust gas analyser for different gaseous species are given in Table 1.

Performance and emissions tests were conducted to evaluate the suitability of different emulsions (M/J and M/K), which were blended with diesel in 1:3 blending ratio as test fuels for diesel engine. Performance test included measurement of brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and exhaust gas temperature (EGT) at different engine operating conditions. The emissions test included measurements of smoke opacity, $CO_2$, CO, HC, and $NO_x$ at different engine loads at constant engine speed of 1500 rpm. The tests were also conducted using mineral diesel as fuel to generate baseline data.

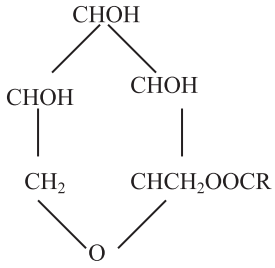


**Fig. 1.** Chemical structure of the surfactant [18].

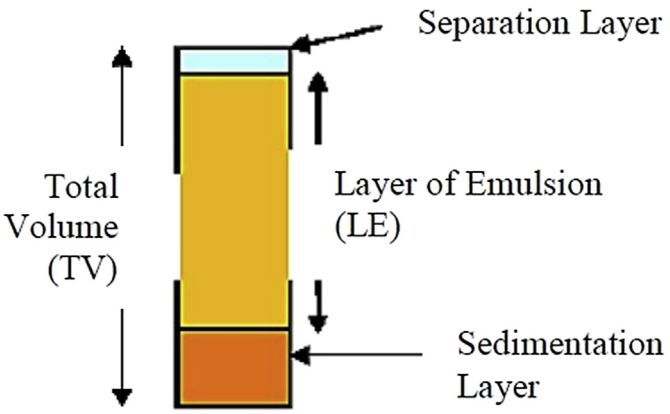


**Fig. 2.** Measurement of relative volume of emulsion [20].

## 3. Results and discussion

Based on the objectives of the study, an experimental plan was prepared. Emulsified test fuels were prepared and properties were evaluated and compared with baseline mineral diesel. Emulsions were then blended with mineral diesel in 1:3 ratio. Performance and emissions tests were conducted on a diesel engine using these blended fuels and relevant engine data were collected. In the reaction stage, factors that greatly influenced the yield and quality were the molar ration of methanol to oil and catalyst concentration [21]. The results are shown in following sub-sections: (i) Emulsification results and fuel characterization, and (ii) Engine performance and emissions characteristics.

### 3.1. Emulsification results and fuel characterization

Previous studies [22] reported that there were many problems associated with using vegetable oils as fuel in CI engines, mainly because of high viscosity of vegetable oils. Large molecular weight and bulky chemical structure of SVO molecules is the reason for their higher viscosity, which cause serious problems in the engine, especially related to fuel pumping, and spray atomization in the FIE systems, finally leading to inferior combustion and emissions. Stable emulsions of 5%, 10%, and 15% (v/v) Methanol in Jatropha oil (M/J) and Methanol in Karanja oil (M/K) were prepared. The stability of these emulsions was checked by measuring the relative volume of emulsion over a period of 7 days. Process variables such as stirrer speed, surfactant concentration and stirring duration were optimised (Figs. 4–6) for given constituents for a certain observation period.

#### 3.1.1. Effect of surfactant concentration

The surfactant concentration was increased from 0.25% to 1.50% for each emulsion and their stability was investigated over 7 days period. Fig. 4 shows that the relative volume of 10% M/J emulsion first increased with increasing surfactant concentration and after obtaining a peak, it decreased.

The emulsion was most stable around the peak because it gave maximum relative volume. At lower surfactant concentrations, emulsion was not so stable due to agglomeration of methanol droplets however at higher surfactant concentrations, the emulsion destabilized because of sedimentation of surfactant and rapid

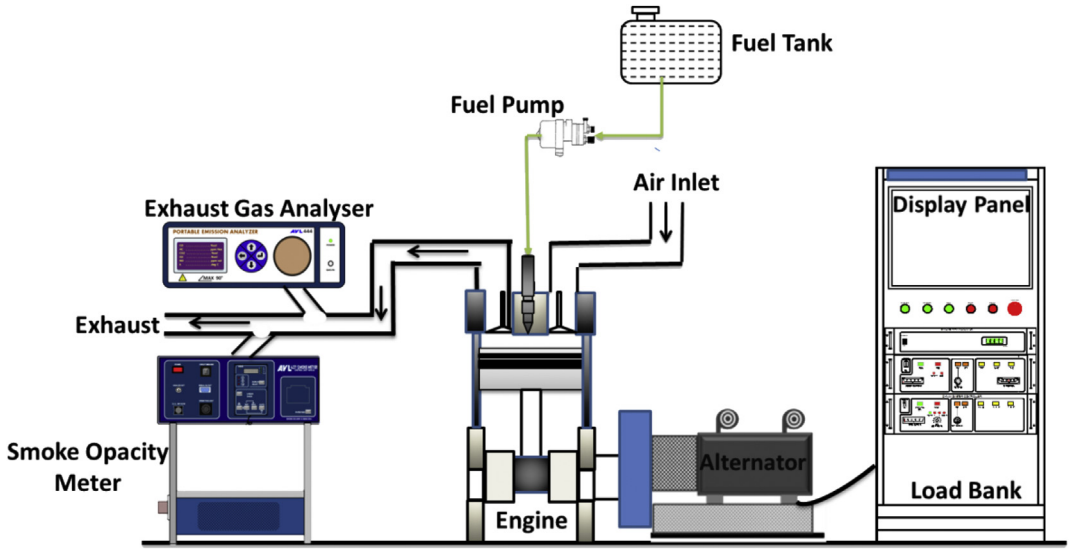


**Fig. 3.** Schematic of the experimental setup.

**Table 1**
Specifications of the exhaust gas analyzer.

| Exhaust species | Measurement range | Resolution |
|---|---|---|
| CO | 0–10 vol% | 0.01 vol% |
| HC | 0–20,000 ppm | 1 ppm |
| $CO_2$ | 0–20 vol% | 0.1 vol% |
| $O_2$ | 0–22 vol% | 0.01 vol% |
| $NO_x$ | 5000 ppm | 1 ppm |

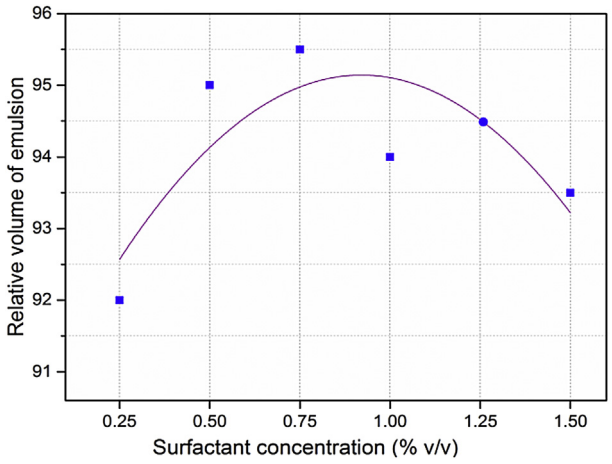


**Fig. 4.** Effect of surfactant concentration for 10% M/J emulsion after 7 days retention time.

coalescence [19]. The optimal surfactant dosage for M/K and M/J emulsions was around the peak.

### 3.1.2. *Effect of stirrer speed*

During emulsification, the interfacial area between two liquids increase. Liquids tend to minimize this surface area therefore mechanical energy is required for emulsification process to proceed.

The emulsions destabilizes upon ageing, particularly in absence of mechanical energy input. The purpose of stirring is to form a stable and homogeneous emulsion, and stirring assists by breaking larger liquid droplets into smaller droplets. From Fig. 5, it is clear that optimum stirrer speed is around the peak of the figure for both, M/K and M/J emulsions.

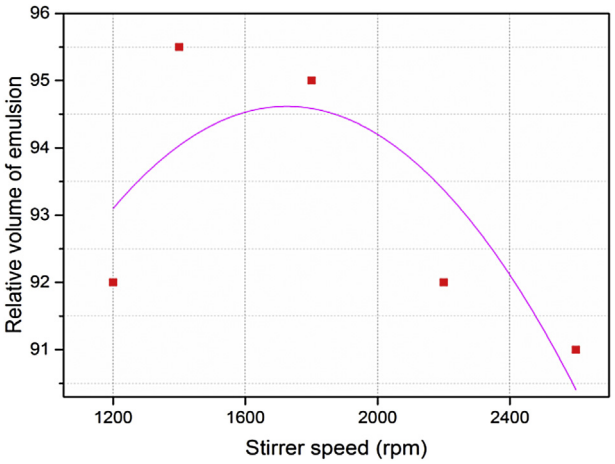


**Fig. 5.** Effect of stirrer speed for 10% M/J emulsion after 7 days retention time.

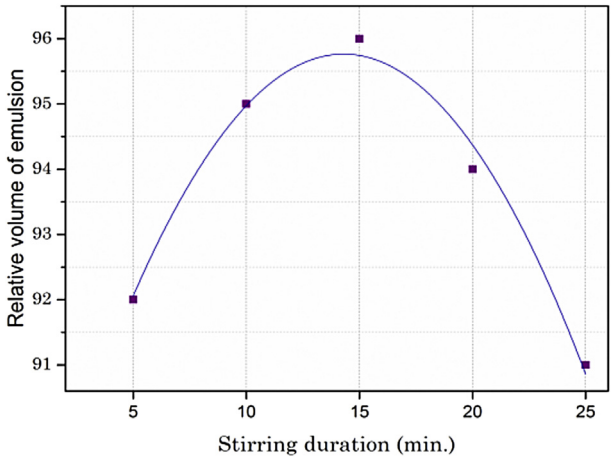


**Fig. 6.** Effect of stirring duration for 10% M/J emulsion after 7 days retention time.

### 3.1.3. Effect of stirring duration

Fig. 6 shows that relative volume of emulsion increases with increasing stirring duration from 5 to 10 min and it reaches maxima either for 15 min or 20 min stirring duration.

As the mixing time increased further, emulsion stability decreased. It means that the emulsifier became more effective with increased mixing time but for very high mixing time; the effectiveness of surfactant decreased because intense stirring caused the surfactant to drop out of the emulsion interface [23].

For optimising the entire spectrum of emulsions, as discussed earlier, detailed tests were conducted to determine relative volume of emulsions for different constituents and observations were recorded every day of the week by varying all emulsification variables, namely surfactant concentration, stirrer speed and stirring duration. The relative volume of emulsions were recorded and plotted in Figs. 7–9. From these figures, it can be noted that the effect of surfactant concentration, stirrer speed and stirring duration followed similar trend as shown in Figs. 4–6.

From Figs. 7–9, it can be noted that the relative volume of emulsions for 1200 rpm stirrer speed decreased sharply with time, indicating that 1200 rpm stirrer speed was not sufficient for stable emulsion formation. A stirrer speed higher than 2200 rpm was however not required because higher stirrer speeds led to surfactant breaking away from the methanol-oil interface either due to excessive mechanical energy input or breaking of fat content of the oils. Fig. 8 shows that 0.75% (v/v) surfactant concentration at 1400 rpm stirrer speed for 15 min stirring duration gave most suitable emulsion for 10% M/J emulsion. In the same way, most suitable emulsification parameters for all test emulsions were chosen from Figs. 7–9, and the summary is tabulated in Table 2.

### 3.1.4. Characterization of emulsions

The emulsions were analysed for important fuel properties such as density, viscosity and lower calorific values (LCV) and results were given in Fig. 10.

The density and LCV of these emulsions was very close to mineral diesel however the kinematic viscosity (6–7 cSt) was relatively higher than mineral diesel (2.7 cSt) (Fig. 10). The viscosity of emulsion further reduced when diesel-emulsion blend was prepared for conducting the engine tests. Methanol blended with diesel due to its fuel properties such as kinematic viscosity and density increased with blending ratio and calorific value decreased [24]. It is reported that emulsified diesel fuels had marginally higher bulk modulus of compressibility, which resulted in marginally earlier fuel injection in case of emulsions compared to baseline mineral diesel. However, this was compensated by the increased ignition delay induced by moisture content in the emulsion [25] therefore emulsified fuels can be employed in diesel engines without changing FIE settings/calibration.

## 3.2. Engine performance and emissions characteristics

All emulsions were blended with mineral diesel in 1:3 ratio and then used as fuel in a single-cylinder compression ignition engine for engine performance and emissions characterisation vis-à-vis baseline mineral diesel. The engine operated very well with these emulsified blends and engine sound was found to be almost similar as that of baseline mineral diesel, once the engine thermally stabilised. Experimental data was acquired from the engine after ensuring thermal stabilization of the engine for 30 min at each load. The data were analysed and results were plotted. These results of engine performance and emissions characteristics are discussed in the following sub-sections.

### 3.2.1. Performance characteristics

Engine performance characteristics evaluated in this

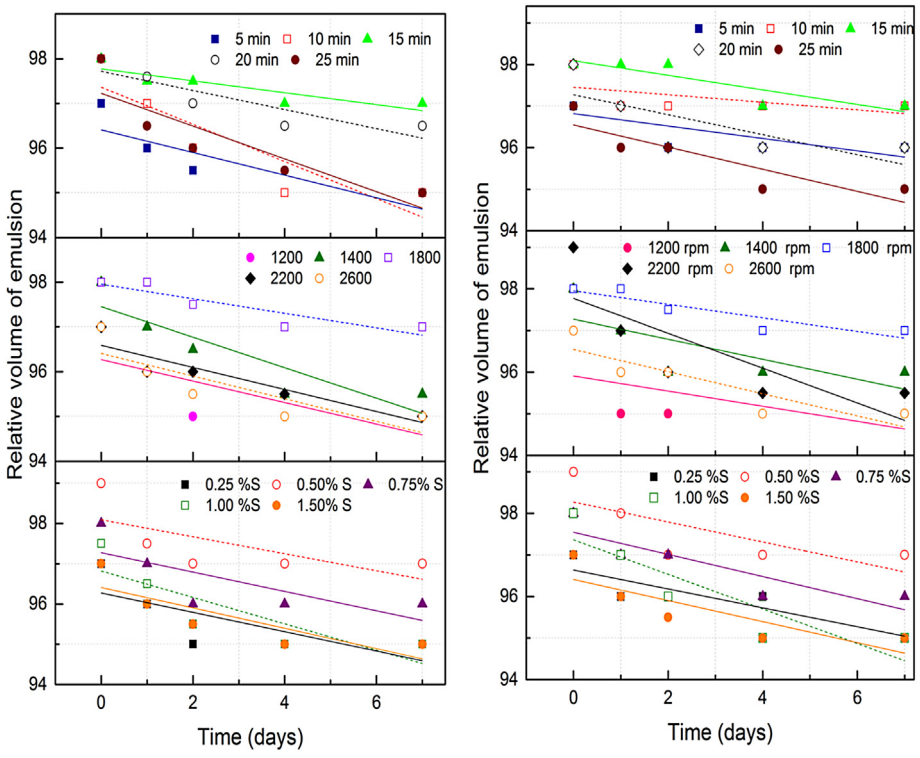


**Fig. 7.** Effect of emulsification parameters on (a) 5% M/K and (b) 5% M/J emulsions.

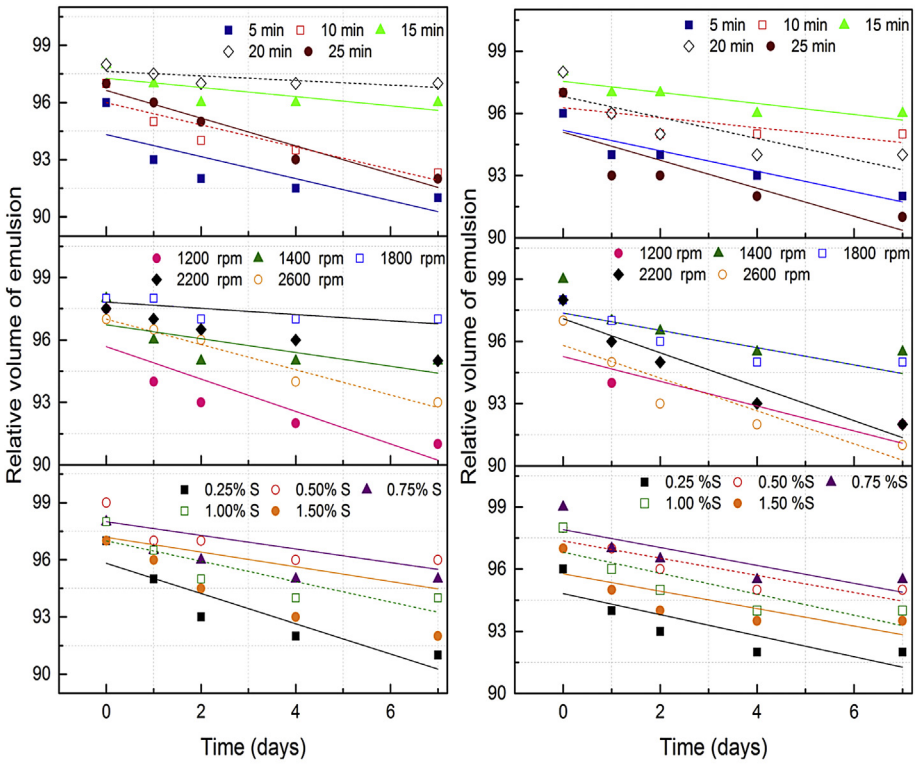


**Fig. 8.** Effect of emulsification parameters on (a) 10% M/K and (b) 10% M/J emulsions.

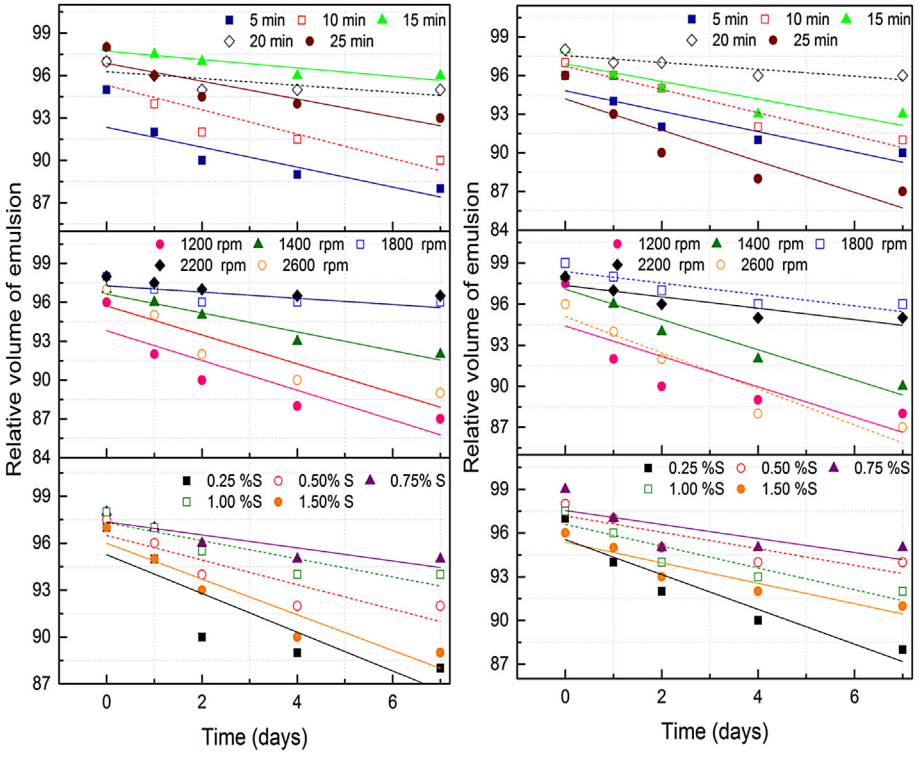


**Fig. 9.** Effect of emulsification parameters on (a) 15% M/K and (b) 15% M/J emulsions.

**Table 2**
Optimum emulsification parameters for M/K and M/J emulsions.

| Emulsion | Optimum parameters | | |
|---|---|---|---|
| | Surfactant concentration (% v/v) | Stirrer speed (rpm) | Stirring duration (min) |
| 5% M/K | 0.50 | 1800 | 15 |
| 10% M/K | 0.50 | 1800 | 20 |
| 15% M/K | 0.75 | 2200 | 20 |
| 5% M/J | 0.50 | 1800 | 15 |
| 10% M/J | 0.75 | 1400 | 15 |
| 15% M/J | 0.75 | 1800 | 20 |

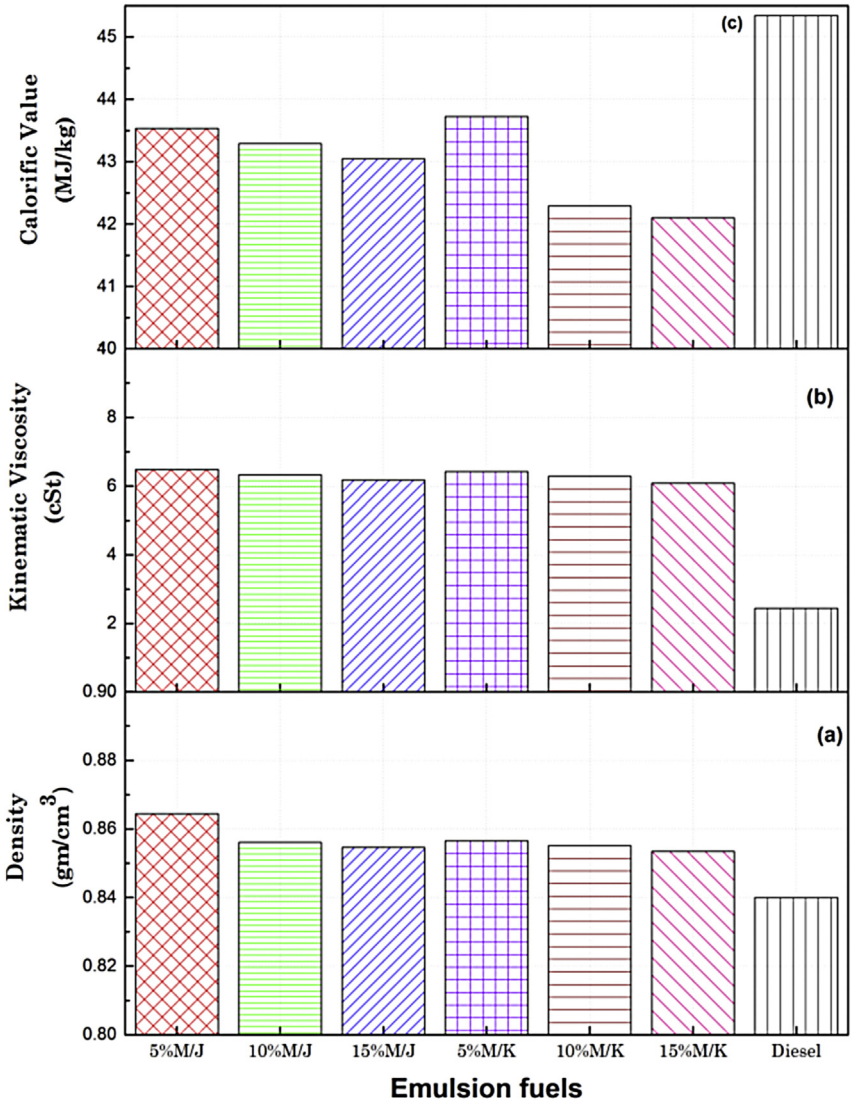


**Fig. 10.** Important properties of test fuels (a) Density (b) Kinematic viscosity and (c) Calorific value.

experimental study included brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and exhaust gas temperature (EGT) (Fig. 11).

BSFC decreased with increasing engine load. At low loads, heat loss to the combustion chamber walls were significantly greater, resulting in higher specific fuel consumption for the useful power produced. BSFC was found to be higher for increasing methanol fraction in the emulsified fuel blends. As the percentage of the methanol in emulsion increased, the density and lower calorific value of fuel decreased, requiring higher fuel quantity to be injected for similar power output. He et al. [26] also reported higher BSFC in an emulsion fuelled diesel engine. BTE decreased with increasing methanol content in the emulsion however the difference was not significant upto 1.5 kW load and the maximum difference was <2% in case of MK15 emulsified blend. Combustion started earlier in test fuels with higher alcohol content compared to mineral diesel and vice-versa [27]. Earlier start of combustion caused higher heat loss during upward movement of piston. This resulted in relatively lower power output, hence marginally lower BTE. MJ10 followed the thermal efficiency curve of mineral diesel quite closely. This was

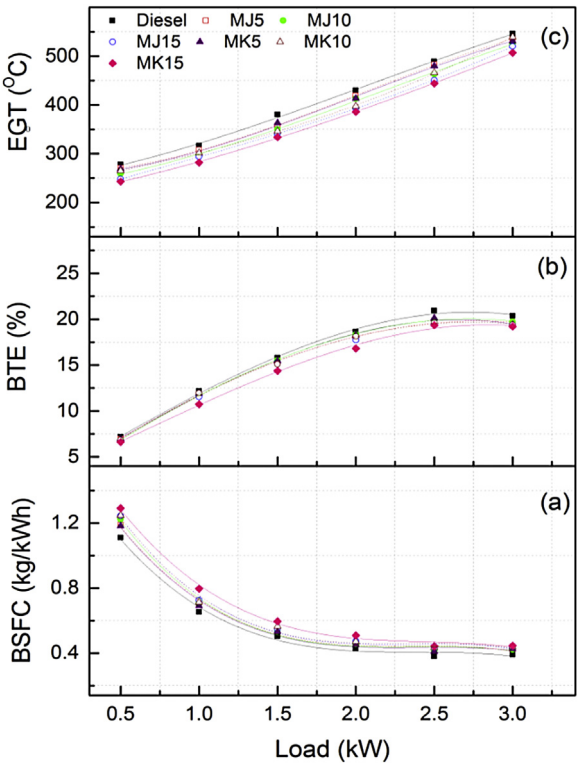


**Fig. 11.** BSFC, BTE, and EGT of emulsified fuels.

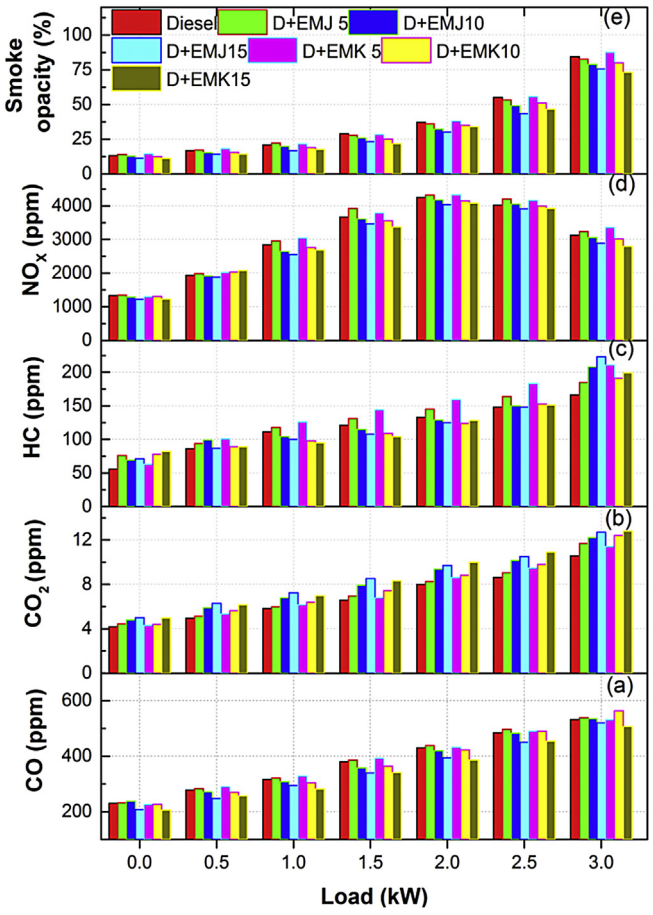


**Fig. 12.** CO, $CO_2$, HC, NOx emissions and smoke opacity of emulsified fuels.

due to relatively higher BSFC of the emulsified fuel compared to mineral diesel. EGT increased with increasing engine load. EGT of emulsified test fuels was lower than baseline mineral diesel but the difference was less than 10% lower at all test conditions. EGT decreased as the percentage of methanol in the emulsion increased, however the difference was not significant. Higher latent heat of methanol cooled the charge at the end of compression stroke because of evaporation of methanol, and average temperature of the cylinder contents decreased as the percentage of methanol in the emulsified fuel increased, leading to relatively lower peak combustion chamber temperature therefore relatively lower EGT.

### 3.2.2. Emission characteristics

Fig. 12 shows emissions characteristics of emulsified fuels vis-a-vis baseline mineral diesel.

CO emissions from the emulsified fuel blends were comparable to baseline mineral diesel at low and moderate engine loads but they were marginally higher at high engine loads for emulsions having higher methanol content. Higher CO emissions were observed due to relatively lower peak in-cylinder temperatures for higher methanol containing emulsions as explained in previous subsection. Similar trend was also seen for HC emissions. HC emissions increased with increasing engine load, and they also increased with increasing concentration of methanol in the emulsified fuel. The stabilization of emulsified fuel increased with increasing surfactant concentration, emulsification time, and ratio of diesel to emulsion [28]. Methanol increased ignition delay, which resulted in greater degree of incomplete combustion at lower engine loads. Therefore at higher loads, HC emissions were relatively lower for higher blends of methanol in emulsified fuel blends compared to baseline mineral diesel due to higher fuel oxygen in high temperature combustion environment, which re-ignited the HC emissions. $CO_2$ in the exhaust was higher for emulsified fuel blends at all loads compared to baseline mineral diesel and it increased with methanol content in the emulsion. Emulsified fuels burns less efficiently (Fig. 10) inspite of being oxygenated, resulting in higher $CO_2$ emissions compared to baseline mineral diesel. $NO_x$ emissions from the engine increased with increasing engine load. This is because increasing engine load reduced ignition delay and increased peak cylinder pressure, temperature and fuel consumption. Emulsified blends produced lower NOx emissions compared to diesel at all loads. Evaporation of methanol and its high latent heat reduced local adiabatic flame temperature and this difference increased with increasing concentration of methanol in the emulsion (as shown in Fig. 10). Additionally traces of moisture in emulsified blends also suppress thermal $NO_X$ production [29]. Lower smoke opacity was observed from emulsified fuel blends compared to baseline mineral diesel. Smoke opacity decreased with increasing methanol concentration in emulsified blends. This was due to micro-explosion phenomenon experienced in the emulsified test fuels, which breaks larger fuel droplets into finer fuel droplets thus enhancing fuel–air mixing in the combustion chamber significantly [29,30]. This helps in reducing formation of soot and $NO_x$ simultaneously, without worrying about PM-$NO_x$ trade-off. Different biofuel blends significantly alter the in-cylinder combustion process due to bulk changes in fuel atomization and fuel-air mixing processes [31]. Also CO and $NO_X$ emissions change, which follow a trend. Additionally, increased concentration of OH radicals from methanol dissociation also reduced soot formation because higher radical concentration promotes oxidation of carbon, resulted in limiting availability of carbon for formation of soot precursors.

## 4. Conclusions

Stable emulsions of methanol, and Jatropha/ Karanja oil with varying methanol concentration [5%, 10%, and 15% (v/v)] were produced. Methanol was in the dispersed phase, vegetable oils were the continuous phase and sorbitan monooleate 'Span80' was used as a surfactant. The emulsion destabilized with time due to agglomeration, sedimentation and rapid coalescence of methanol droplets. Experiments were conducted to optimise process variables such as surfactant concentration, stirrer speed and stirring duration for various emulsions. The optimum surfactant concentration for M/K and M/J emulsions was 0.5%–0.75% (v/v); optimum stirrer speed was 1800–2000 rpm for M/K emulsion and 1400–1800 rpm for M/J emulsion; and optimum stirring duration was 15–20 min. Emulsions exhibited important fuel properties comparable to mineral diesel. Emulsions were blended with diesel in 1:3 (v/v) ratio and then evaluated in a single cylinder diesel engine for their performance and emission characteristics. Performance and emission characteristics of emulsified fuel blends were directly related to methanol concentration in the dispersed phase of the emulsion. Brake thermal efficiency of emulsified blends was slightly lower and Brake specific fuel consumption was slightly higher than baseline mineral diesel. Exhaust gas temperature was slightly lower than baseline mineral diesel. CO and HC emissions from the emulsified blends were comparable to baseline mineral diesel at low and moderate loads, while it was higher at higher loads due to incomplete combustion. Smoke opacity and $NO_x$ emissions reduced with increasing concentration of methanol in the emulsified blend at almost all loads. It may be therefore concluded that the emulsified blends of vegetable oils with methanol can substitute mineral diesel as a partial substitute in single cylinder diesel engine, typically used in agriculture sector and decentralised power generation sector, without any modification in engine hardware.

## References


[1] R.C. Costa, J.R. Sodré, Compression ratio effects on an ethanol/gasoline fuelled engine performance, Appl. Therm. Eng. 31 (2011) 278–283.
[2] MNRE (Ministry of New and Renewable Energy), report, 2008. http://mnre.gov.in/file-manager/annual-report/2008-2009/EN/introduction.htm.
[3] L.M. Chum, R.P. Overend, Biomass and renewable fuel, Fuel Bioprocess. Technol. 17 (2001) 187–195.
[4] MOPNG, Annual Report 2013–2014, Ministry of Petroleum and Natural Gas, Government of India, New Delhi, 2014. http://petroleum.nic.in/docs/Annual_Report.AR13-14.pdf.
[5] P.C. Badger, Ethanol from Cellulose: a General Review, Trends in New Crops and New Uses, 2002, pp. 17–21.
[6] R.J. Crookes, F. Kiannejad, M.A.A. Nazha, Systematic assessment of combustion characteristics of biofuels and emulsions with water for use as diesel engine fuels, Energy Conserv. Manag. Rev. 15 (38) (1997) 1785–1795.
[7] K. Biplab, N. Debnath, K.S. Ujjwal, S. Niranjan, A comprehensive review on the application of emulsions as an alternative fuel for diesel engines, Renew. Sustain. Energy Rev. 42 (2015) 196–211.
[8] S. Jain, M.P. Sharma, Prospects of biodiesel from Jatropha in India: a review, Renew. Sustain. Energy Rev. 14 (2) (2010) 763–771.
[9] N.J. Barsic, A.L. Humke, Performance and Emissions Characteristics of a Naturally Aspirated Diesel Engine with Vegetable Oil Fuels, no. 810262. SAE Technical Paper, 1981.
[10] M.K. Senthil, A. Kerihuel, J. Bellettre, M. Tazerout, Experimental investigations on the use of preheated animal fat as fuel in a compression ignition engine, Renew. Energy 30 (9) (2005) 1443–1456.
[11] Y.S. Lin, H.P. Lin, Spray characteristics of emulsified castor biodiesel on engine emissions and deposit formation, Renew. Energy 36 (2011) 3507–3516.
[12] Y. Ali, M.A. Hanna, L.I. Leviticus, Emissions and power characteristics of diesel engines on methyl soyate and diesel fuel blends, Bioresour. Technol. 52 (2) (1995) 185–195.
[13] A. Kerihuel, M.K. Senthil, J. Bellettre, M. Tazerout, Ethanol animal fat emulsions as a diesel engine fuel-part 1: formulations and influential parameters, Fuel 85 (17) (2006) 2640–2645.
[14] A. Kerihuel, M.K. Senthil, J. Bellettre, M. Tazerout, Investigations on a Compression Ignition Engine Using Animal Fat and Its Emulsions with Water and Methanol as Fuel, no. 2005-01-1729. SAE Technical Paper, 2005.
[15] C.Y. Lin, K.H. Wang, Effects of an oxygenated additive on the emulsification characteristics of two and three phase diesel emulsions, Fuel 83 (4) (2004) 507–515.
[16] M.Z. Abu, Performance of single cylinder-direct injection diesel engine using water fuel emulsions, Energy Convers. Manag. 45 (2003) 697–705.
[17] J.H. Lee, J.G. Choi, Y.S. Kim, K.R. Kim, S.W. Kim, D.K. Oh, Enhancement of retinal production by supplementing the surfactant Span 80 using metabolically engineered Escherichia coli, J. Biosci. Bio Eng. 113 (4) (2012) 461–466.
[18] R.K. Pandey, A. Rehman, R.M. Sarviya, Impact of alternative fuel properties on fuel spray behavior and atomization, Renew. Sustain. Energy Rev. 16 (2012) 1762–1778.
[19] Z. Guo, S. Wang, X. Wang, Stability mechanism investigation of emulsion fuels from biomass pyrolysis oil and diesel, Energy 66 (2014) 250–255.
[20] G. Chen, D. Tao, An experimental study of stability of oil-water emulsion, Fuel Process. Technol. 86 (5) (2005) 499–508.
[21] S. Sinha, A.K. Agarwal, S. Garg, Biodiesel development from rice bran oil: transesterification process optimization and fuel characterization, Energy Convers. Manag. 49 (2008) 1248–1257.
[22] A.K. Agarwal, Vegetable oils versus diesel fuel: development and use of biodiesel in a compression ignition engine, TIDE 8 (3) (1998) 191–204.
[23] S.V. Verbich, S. Dukhin, A. Tarovski, O. Holt, O. Sather, J. Sjoblom, A Physicochemical and Engineering Aspects: Colloids and Surfaces, no. 123-124, 1997, pp. 209–223.
[24] M. Mofijura, H.H. Masjukib, M.A. Kalamb, M.G. Rasula, A.E. Atabanic, M.A. Hazrata, H.M. Mahmuduld, Effect of biodiesel-diesel blending on physico-chemical properties of biodiesel produced from Moringa oleifera, Procedia Eng. 105 (2015) 665–669.
[25] B.Q. He, S.J. Shuai, J.X. Wang, H. He, The effect of ethanol blended diesel fuels on emissions from a diesel engine, Atmos. Environ. 37 (35) (2003) 4965–4971.
[26] O. Armas, R. Ballesteros, F.J. Martos, J.R. Agudelo, Characterization of light duty diesel engine pollutant emissions using water-emulsified fuel, Fuel 84 (2005) 1011–1018.
[27] R.K. Maurya, A.K. Agarwal, Experimental investigation of the effect of the intake air temperature and mixture quality on the combustion of a methanol and gasoline-fuelled homogeneous charge compression ignition engine, Proc. Inst. Mech. Eng. Part D J. Automob. Eng. 223 (11) (2009) 1445–1458.
[28] W. Jiao, Y. Wang, X. Li, C. Xu, Y. Liu, Q. Zhang, Stabilization performance of methanol-diesel emulsified fuel prepared using an impinging stream-rotating packed bed, Renew. Energy 85 (2016) 573–579.
[29] T. Kadota, H. Yamasaki, Recent advances in the combustion of water fuel emulsion, Prog. Energy Combust. Sci. 28 (5) (2002) 385–404.
[30] H. Masjuki, M.Z. Abdulmuin, H.S. Sii, Indirect injection diesel engine operation on palm oil methyl esters and its emulsions, Proc. Inst. Mech. Eng. Part D J. Automob. Eng. 211 (4) (1997) 291–299.
[31] A.K. Agarwal, A. Dhar, Experimental investigations of performance, emission and combustion characteristics of Karanja oil blends fuelled DICI engine, Renew. Energy 52 (2013) 283–291.