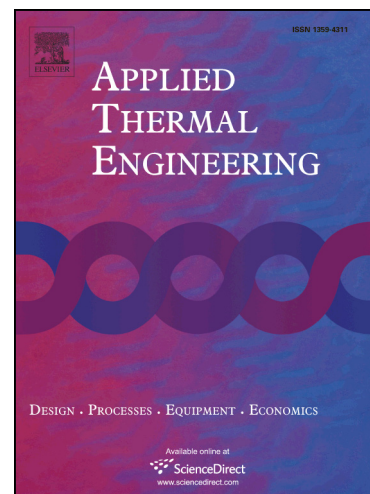# Accepted Manuscript

Research Paper

Effect of emulsified fuels based on fatty acid distillates on single cylinder diesel engine performance and exhaust emissions

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Effect of emulsified fuels based on fatty acid distillates on single cylinder diesel engine performance and exhaust emissions

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Abstract:

In this contribution an experimental investigation concerning the effect of emulsified fuels based on fatty acid distillates (FAD) on a single cylinder diesel engine performance and exhaust emissions was investigated. The single cylinder diesel engine assessment was conducted under selected test conditions, fixing the engine speed and varying the load. Emulsified fuels were formulated using blends of fatty acid distillates in diesel fuel as continuous phase, as well as deionized water as dispersed phase and Nonyl phenol with 8 moles of ethylene oxide as surfactant. Over these conditions the brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), ignition delay (ID), rate of heat release (ROHR), cumulative heat release, nitrogen oxides (NOx), carbon monoxide (CO) and unburned hydrocarbons (HC) were analyzed. The results indicate that the use of emulsified fuels produce increases in the specific fuel consumption and decreases in the brake thermal efficiency for emulsions compared to diesel fuel and a blend of 30% FAD in diesel. On the other hand, later starts of combustion and retarded ROHR for emulsified fuels compared to diesel fuel and a blend of 30% FAD in diesel were obtained. Further, lower NOx and higher HC and CO emissions for emulsified fuels were reported.

Keywords: Emulsified fuel, fatty acid distillates, waste by-product, engine performance, exhaust emissions

1. Introduction

Biofuel production from vegetable oils is widely considered one of the most sustainable alternatives to diesel fuel. However, they are not economically competitive as yet due to their current production and supply chain (i.e. price, manufacturing, supply and distribution). In this context, biofuels production based on waste and residual by-products represents an attractive alternative due to low waste product costs.

The fatty acid distillates (FAD) are a low-value by-product obtained from the vegetable oil refining industry generated during the physical refining in the fatty acid stripping and deodorization stages [1]. It is a well-known fact that several metric tons of fatty acid distillates are produced around the world annually from different feedstock (e.g. palm oil, rapeseed and soybean oil). Particularly, Malaysia has one of the largest refining palm oil industries in the world [2] and hundreds of thousands of metric tons of fatty acid distillates are annually generated according to Malaysian Oil Palm Statistics [3].

According to the fatty acid distillates' composition they are suitable as a feedstock for biofuel production [1, 4-9]. This element might enhance the refining industry efficiency; contributing to the concept of zero-waste through recycling, generating energy and reducing the environmental degradation. However, fatty acid distillates have not been researched thoroughly and they are not widely applied as diesel engine fuel.

The direct use of vegetable oils, animal fats or waste by-products such as FAD as diesel engine fuel affects the engine performance and component wear. To obtain an economic and environmentally-friendly engine fuel from fatty acid distillates, it is necessary to change their physicochemical properties for which there are different methods (preheating, blending, trans/esterification, cracking/pyrolysis and emulsification). Even, it is also possible to use an additive as fuel improver to enhance the engine performance and emissions [10-13].

Among these methods the transesterification is one of the most popular methods. However, because of the high free fatty acid (FFA) content of FAD, this feedstock cannot be converted directly to biodiesel via alkaline transesterification [14]. Although different methods to decrease the FFA content are reported [15-17] for enhancing the transesterification efficiency, biodiesel production is not economically profitable until now. In addition, depending on the quality of the FAD feedstock, additional steps are necessary to remove the water content and free fatty acids.

The combination of different methods previously mentioned might represent an alternative. The use of blend of fatty acids distillates in diesel fuel can leads to a reduction of viscosity to within biodiesel and diesel fuel standards. Thereupon, the emulsification technique has an additional attraction linked to the emulsified fuel capacity of decreasing diesel engine exhaust emissions such as nitrogen oxides (NOx). Both methods are not sophisticated because modifications of the original engine design and special equipment are not necessary.

The formulation of an emulsion involves no complex chemical reactions [18]. In addition, due to the micro-explosion phenomenon as a consequence of the dispersed water into emulsified fuel, it is also possible to improve the atomization process and recover in part the combustion efficiency when it is used as diesel engine fuel.

A significant number of investigations on emulsified fuels formulation and engine performance using vegetable oil sourced fuels as feedstock have been conducted since the 20th century to the present [19-36]. However, emulsified fuels containing fatty acid distillates as alternative fuels have not been reported. Therefore, in the present work we aimed for the formulation of emulsified fuels containing diesel fuel and fatty acid distillates from the local refining oil industry in order to analyze their effect on diesel engine performance and exhaust emissions.

2. Materials and Methods

2.1 *Emulsified fuels formulation*

The emulsified systems were formulated based on stabilization zone reported in our previous experiments [37] using blends of rapeseed oil in diesel fuel as continuous phase. Additional components such as deionized water as dispersed phase and Nonyl phenol (NP) + 8 moles of ethylene oxide (8MOE) as surfactant were used. The fatty acid distillates (FAD) were collected from the Cuban vegetable oil refining industry. The physicochemical properties of diesel fuel and fatty acid distillates are shown in Table 1.

Table 1
Physicochemical properties of diesel fuel and fatty acid distillates

Properties	Unit	Diesel fuel	Fatty acid distillates
Viscosity	mm^2/sec	5	28.6
Density	g/cm^3	0.818	0.908
Lower heating value	MJ/kg	42.5	36.3
Water content	%	<0.05	0.387
Cetane number	-	45	40*

*Prediction using Sánchez' model [38]

The fatty acid distillates were filtered to remove impurities. For this purpose a vacuum pump coupled to a Kitasato flask attached to a Büchner porcelain funnel through a rubber adapter was used. The filter paper had a medium filtered speed. The vacuum pump was a rotary vane pump MLW DSE2 with a pressure of 5.7*Pa* and pumping rate of *2m³/h.*

The emulsification was conducted using a sonicator lab device (i.e.: Soniprep 120) with a frequency of 14 *Hz*. The volume prepared was 250 *mL* with continuous sonication during 15 minutes. The required amount of surfactant was added into the continuous phase (blends of FAD in diesel fuel); then the deionized water was slowly added. After each addition, the dispersed systems were vigorously sonicated.

The stability assessment of emulsified fuels was analyzed through a direct method like the visual observation, keeping the samples in glass test tubes with stopper after their preparation, aging at ambient laboratory conditions. The main criterion for stable emulsified fuels was the preservation of only one phase [39].

Physicochemical properties such as density, dynamic viscosity and lower heating value were evaluated. The density was measured using a pycnometer of 25 *mL*. On the other hand, the dynamic viscosity was evaluated using a viscometer RION VT-03F, with a measurement accuracy of ±5%. The measurements were repeated thrice and the averages of the replicates were used in the analysis. The lower heating value of fuels was performed through a bomb calorimeter according to ASTM D 240.

2.2 *Experimental engine set-up and procedures*

The engine used for the research was a Lister Petter diesel engine PH1W. This is a four-stroke single cylinder engine with direct injection. The main engine characteristics are shown in table 2.

Table 2

Characteristics of the Lister Petter diesel engine PH1W

Item	Value
Bore	87.3 *mm*
Stroke	110 *mm*
Compression ratio	16.5:1
Cubic capacity per cylinder	659 *cm^3*
Fuel injection timing	24° before TDC (up to 1650 *rpm*)
	28° before TDC (1651-2000 *rpm*)
Inlet valve opens	4.5° before TDC
Inlet valve closes	35.5° after BDC
Exhaust valve opens	35.5° before BDC
Exhaust valve closes	4.5° after TDC

TDC: Top dead center, BDC: Bottom dead center

The schematic diagram of the experimental setup used for the engine tests is shown in Figure 1. The engine was equipped with load cell, Froude hydraulic brake DPX 2, four K-type thermocouples and a tachometer (Radio energy). A piezoelectric relative pressure sensor (Kistler; model: 6067C, water-cooled) mounted directly on the cylinder head was used to measure the cylinder pressure. A piezoresistive absolute pressure sensor (4075A10) mounted in the admission duct was used to register the intake air pressure.

1. Diesel engine	5. Tachometer
2. Admission pressure sensor	6. Exhaust gas analyzer
3. Cylinder pressure sensor	7. Control panel
4. Hydraulic brake	8. Fuel tank

9. Digital weight	13. Mechanical encoder
10. Fuel filter	14. Electronic encoder
11. Signal conditioner	15. Pulse multiplier
12. Personal computer	

Fig.1. Schematic diagram of the engine bench setup

The engine was also equipped with a data acquisition system, a Kistler signal conditioning platform with a charge amplifier (model 5064); a piezoresistive amplifier (model 4665), a module NI 9401 (digital) and a module NI 9215-BNC (analog) were used. On the other hand, a Kistler system 2614A to measure the crank angle position was used, with a resolution of 0.2 crank angle degrees (*CAD*). This system provided a correlation between pressure measurement signals and crank angle degrees position.

The assessment of the engine was conducted under selected test conditions fixing the engine speed at 1500*rpm* (to avoid the variation of the injection timing) and varying the load as is shown in table 3. Over these experimental conditions the brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), ignition delay (ID), rate of heat release (ROHR), cumulative heat release and exhaust emissions were analyzed.

Table 3

Engine test conditions

n	Torque	Power output
(*rpm*)	(*Nm*)	(*KW*)
1500	15	2.36
1500	20	3.14
1500	25	3.93
1500	30	4.71

The exhaust emissions were measured using a Testo 350 analyzer. The emissions analyzed were the nitrogen oxide (NOx), carbon monoxide (CO) and unburned hydrocarbons (HC). The fuel mass consumption was analyzed gravimetrically using a Mettler Toledo IND425 weighing scale and a digital stopwatch. The atmospheric conditions were monitored through a TFA station (model: 35.1078.10.IT).

2.3 *Uncertainty analysis on engine measurements*

The accuracy and device specifications used in this research are shown in Table 4.

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Table 4
Summary of accuracy and device specifications

Variable group	Variable	Device	Accuracy
Exhaust emissions	HC	Gas analyzer	±5%
	CO		±5%
	NOx		±5%
Fuel consumption	Fuel flow rate	Weighing scale	±0.001kg
	Time	Digital stopwatch	±0.1sec
Torque	Torque output	Load cell	±0.1N
Speed	Engine speed output	Tachometer	±6 rpm
Angle	Crank angle degree	Encoder mechanic Kistler 2614A1 Encoder electric Kistler 2614A2 Pulse multiplier Kistler 2614B4	±0.2CAD
Pressure	Intake pressure	Kistler 4075A10	±3000 Pa
	Cylinder pressure	Kistler 6067C	±1%

The uncertainty on measurements of crank angle degree and the ignition delay were defined by the resolution of crank angle (i.e.:±0.2CAD) itself. On the other hand, the uncertainties on engine power output (i.e.:±1%), fuel flow rate (i.e.:±1.5%), brake specific fuel consumption (i.e.±2%) and brake thermal efficiency (i.e.±2%) were determined analyzing the propagation of measurement uncertainty.

3. Experimental Results

3.1 Experimental results of emulsified fuels formulation

As was previously mentioned, emulsified fuels were formulated using blends of fatty acid distillates in diesel fuel as continuous phase, as well as deionized water as dispersed phase and Nonyl phenol with 8 moles of ethylene oxide as surfactant. The surfactant percentage was fixed at 4% (by volume) for all emulsified fuels as it was found as a proper amount to ensure stability. Stable dispersed systems with different diesel fuel/FAD ratio and water amount were obtained as is shown in Figure 2. In this ternary diagram, two different zones (stable system in black and non-stable system in white) were drawn.
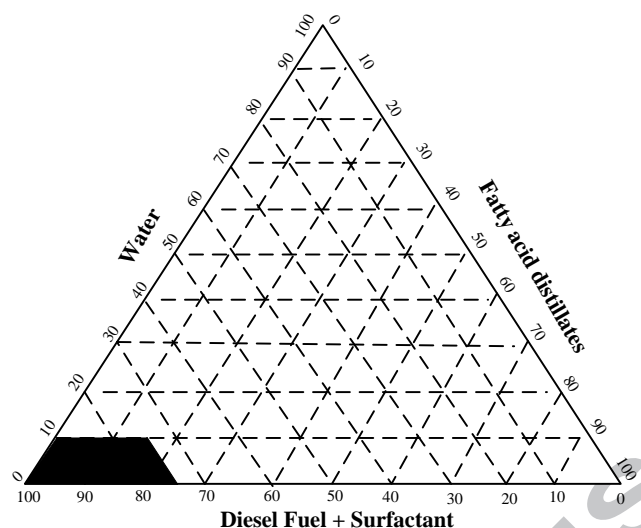
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Fig. 2. Ternary diagram obtained for stable emulsions

The stability time of the emulsified fuels attained 72 *hours* after their preparation. Based on this spontaneous tendency for phase separation and their optical appearance (turbidity appearance like milk), all emulsified fuels were classified as emulsions. In addition, according to their viscosities not all obtained emulsified fuels were suitable for light duty diesel engine applications.

From the previously obtained dispersed systems, two emulsions with higher FAD percentage were selected to test at the engine test bench. The emulsions' selection criteria included the use of the least possible amount of diesel fuel, keeping fixed its percentage (i.e.: 71%), as well as the interest to analyze the influence of the water percentage on engine performance and exhaust emissions. All this, bearing in mind the viscosity range proposed by the biodiesel and diesel standard.

The physicochemical properties of the selected emulsions (EFAD1 and EFAD2) to analyze their effect on a single cylinder diesel engine performance and exhaust emissions are shown in Table 5. An increase of the water percentage led to higher viscosities. However, comparing the density results, a slight difference between emulsions was observed. Finally, differences between emulsions' heating values were expected.

Table 5

Physicochemical properties of fuels tested

Fuel	Diesel (%)	FAD (%)	Water (%)	Viscosity (*mPa·s*)	Density (*g/cm³*)	LHV (*MJ/kg*)
Mix 30%FAD-in diesel	70	30	-	7.2	0.835	40.6
EFAD1	71	22.5	2.5	6	0.850	39.4
EFAD2	71	20	5	6.5	0.853	38.5

EFAD: Emulsified fatty acid distillates, LHV: Lower heating value

3.2. *Brake specific fuel consumption*

The engine was initially run on diesel fuel and a blend of 30% FAD in diesel to generate base line data and after that it was run on emulsified fuels. The results of BSFC are shown in Figure 3. In general, increases of the brake specific fuel consumption were obtained for emulsions compared to diesel fuel and a blend of 30% FAD in diesel. Increase of the water percentage in the emulsions next to the presence of FAD leads to high brake specific fuel consumption. Similar results have been attained for other emulsified fuels [29, 31, 32, 40-44].

The higher BSFC of emulsified fuels is mainly due to their lower heating values compared to other fuels (*see table 1 and table 5*). However, it is important to point out that since water has no contribution to the heating values of the emulsions, it is reasonable to only consider the percentage of fuel used into emulsified fuel in the engine operation [45].
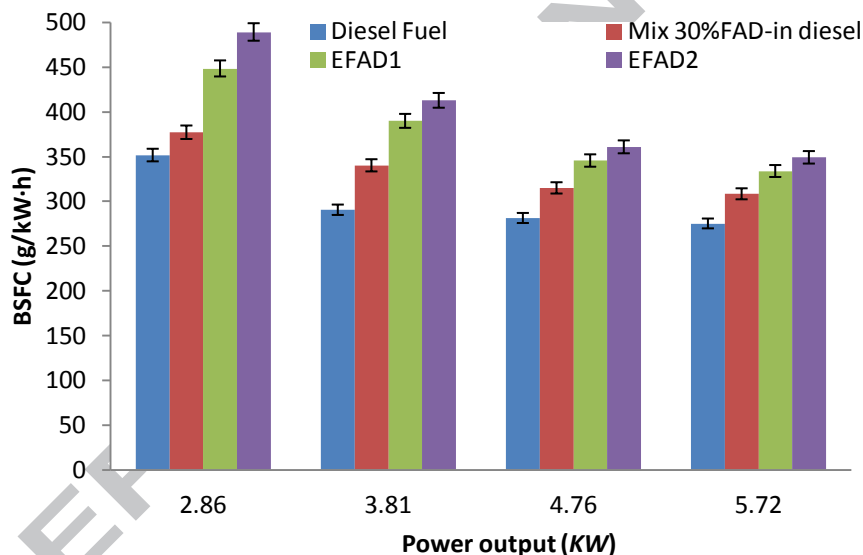
Fig. 3. Brake specific fuel consumption for test fuels

3.2.1. *Brake thermal efficiency*

The variation of the brake thermal efficiency (BTE) is shown in the Figure 4. The BTE increases as the load increases. Decreases of BTE for emulsions compared to diesel fuel were achieved. However, at high load comparable BTE were obtained for emulsified fuels and the blend of 30% FAD in diesel. In addition, an increase of the water percentage into emulsified fuels linked to the presence of FAD resulted in a decrease in BTE, which was also reported by Nanthagopal [35].

The variations in brake thermal efficiency have a close relationship with the physicochemical properties, structure and composition of the emulsified fuels. From the review of the state-of-the-art and current trends, decreases in the BTE of the emulsified fuels have been reported [31, 44, 46, 47]. Nevertheless, an increase in the BTE of emulsified fuels compared to diesel fuel was noticed by Nanthagopal [35].
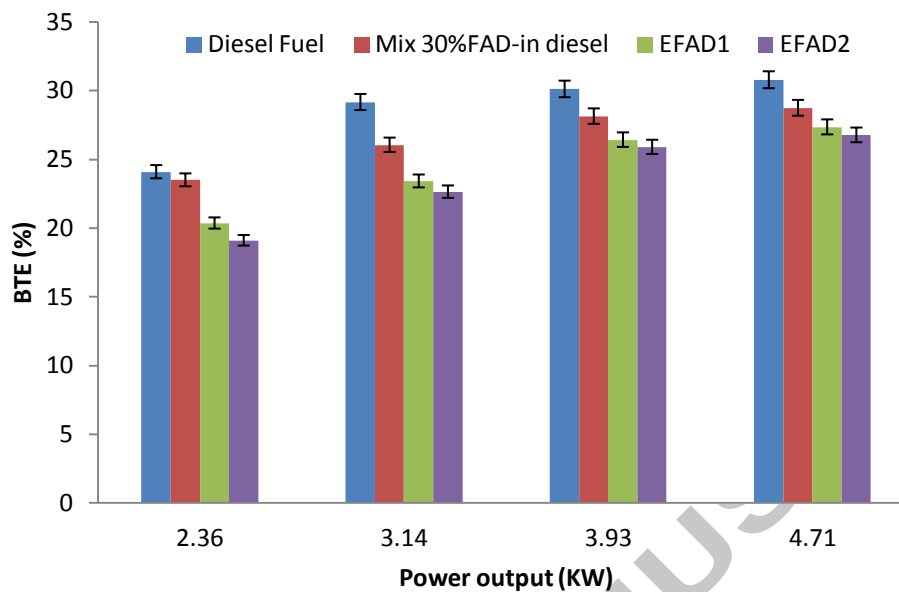
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Fig. 4. Brake thermal efficiency for test fuels

3.2.2. *Ignition delay*

One of the common methods used to determine the ignition delay in diesel engines is analyzing the behavior of cylinder pressure and its first derivative. In this study the start of injection was assumed taking into account the manufacturer specifications (*see table 2*). The start of combustion was fixed at the point where the line of 150000 *Pa/CAD* crosses the graph of the first derivative. A comparison of the ignition delay results are depicted in Figure 5.

Under the experimental conditions, longer ignition delays for emulsified fuels than diesel fuel and its blend in FAD were found. Nevertheless, at highest load condition no significant differences between all test fuels were achieved. This trend is a consequence of two facts: lower cetane number of FAD and dispersed water into emulsified fuel. The thermal effect of the dispersed water is one of the most important thing to take into account because it should play an important role in the atomization process and ignition quality (*e.g. vigorous evaporation, micro-explosion of emulsified droplets, etc.*), bringing a significant variation of ID.
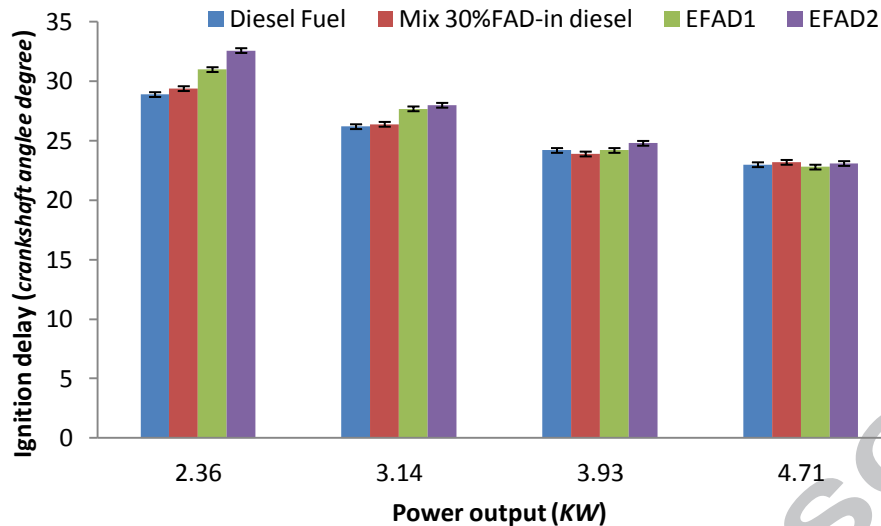
Fig. 5. Ignition delay for test fuels

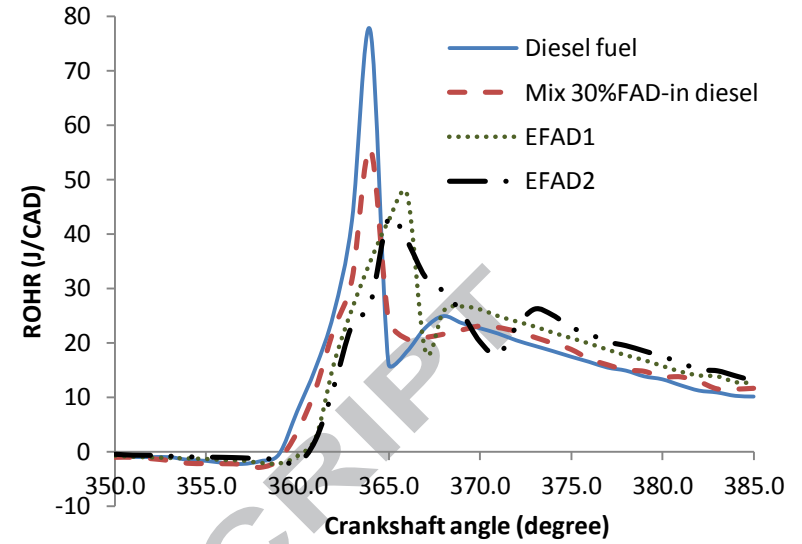### 3.2.3. *Rate of heat release and cumulative heat release*

The rate of heat release was computed from the cylinder gas pressure and instantaneous cylinder volume following the procedure outlined by Heywood [48] and Alagumalai [49]. Figure 6 show the variation of rate of heat release (*ROHR*) under different engine operating conditions for test fuels. The diesel fuel achieved higher peak of ROHR than other fuels, although it is valid to note that at 4.71*KW* comparable peak for emulsified fuels were reached. Also, emulsified fuels at 3.43*KW* and 4.71*KW* reported peak of ROHR comparable to a blend of 30% FAD in diesel.

As was previously reported (see section 3.2.2), later starts of combustion were obtained for emulsified fuels. As a consequence of this fact highest late-cycle heat release rates for emulsified fuels are expected. The presence of water in the emulsified fuels causes variations in the peak of ROHR and shifts in the premixed combustion phase and mixing-controlled combustion phase conforming to a delay of the start of combustion. An important amount of energy during combustion is used by the dispersed water to change the phase (i.e. liquid to vapor). All this brings an important increase of unburned fuel at the later times. In addition, the lower peak achieved is also related with the lower heating content of the emulsions compared to diesel fuel and a blend of 30% FAD in diesel.

A comparison of the cumulative heat release is shown in Fig 7. The cumulative heat release is a relative magnitude calculated as the ratio of the net cumulative heat release and the fuel energy supplied per cycle. In addition, net cumulative heat release was analyzed by integrating the ROHR over the closed part of the engine cycle. As can be noted, emulsified fuels exhibited lowest cumulative energy at lower power output compared to diesel fuel and a blend of 30% FAD in diesel. However, EFAD1 showed slight increases at 3.93*KW* and 4.71*KW*, beside EFAD2 (*only at 4.71KW*) in contrast with diesel fuel results.
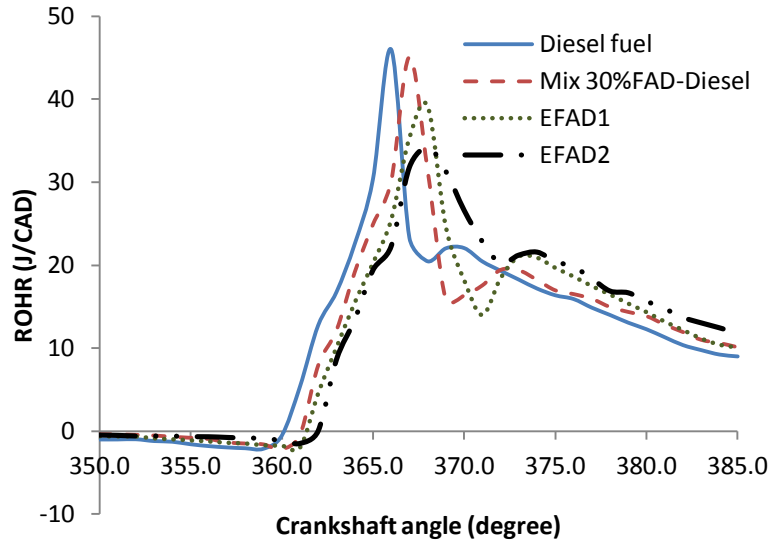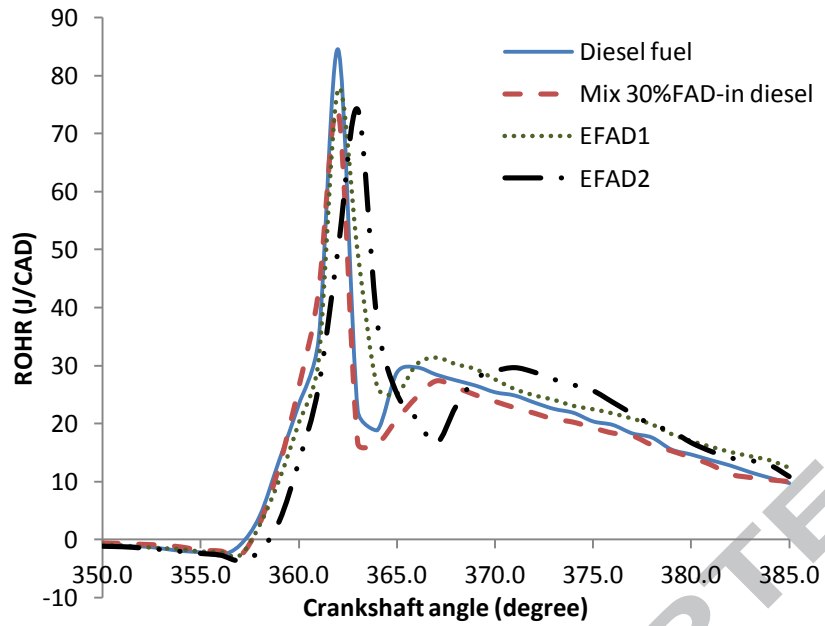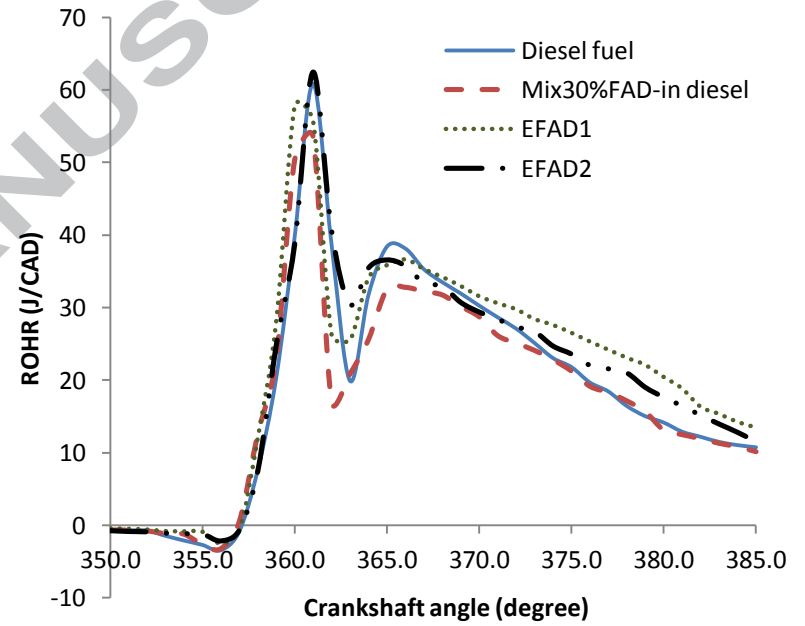
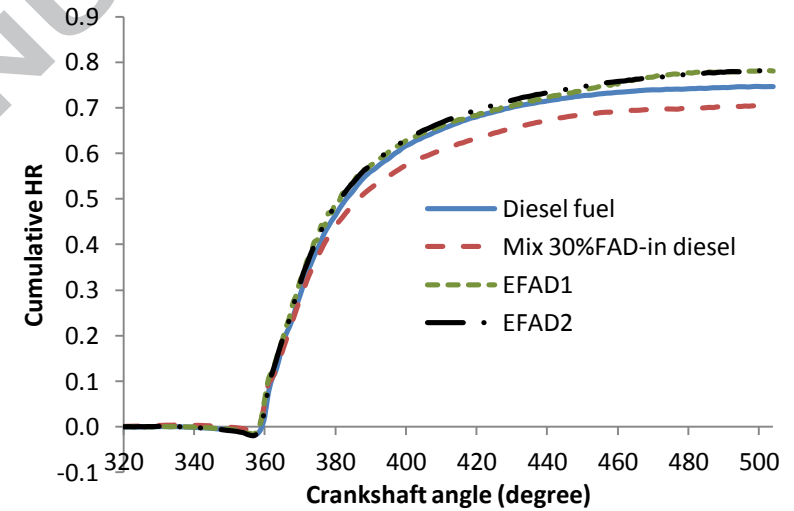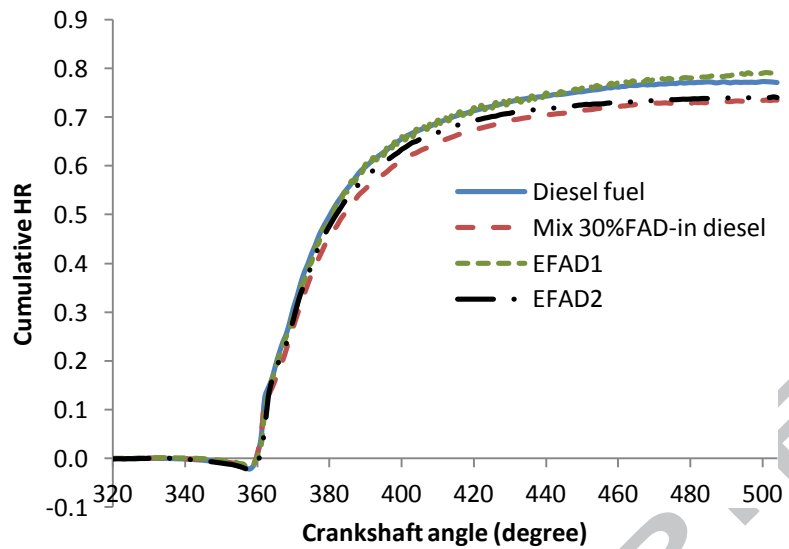Fig. 6. Rate of heat release for test fuels: a)@2.36KW, b) @3.14KW, c) @3.93KW, d) @4,71KW
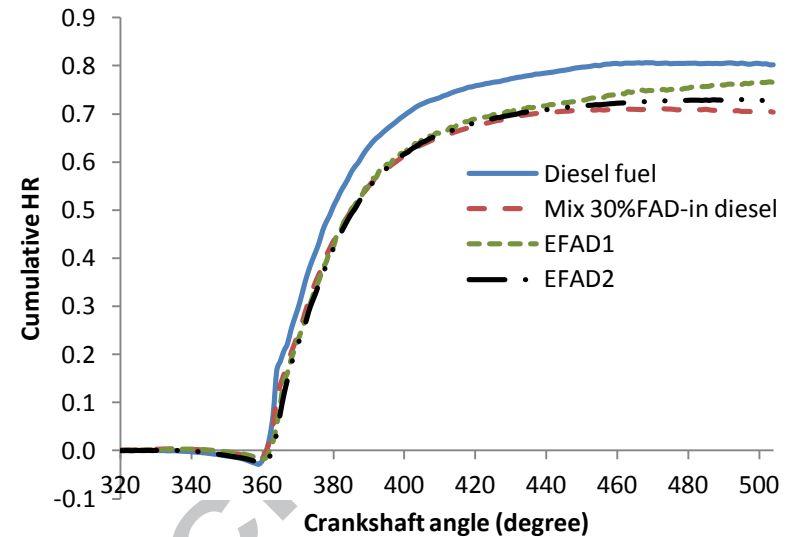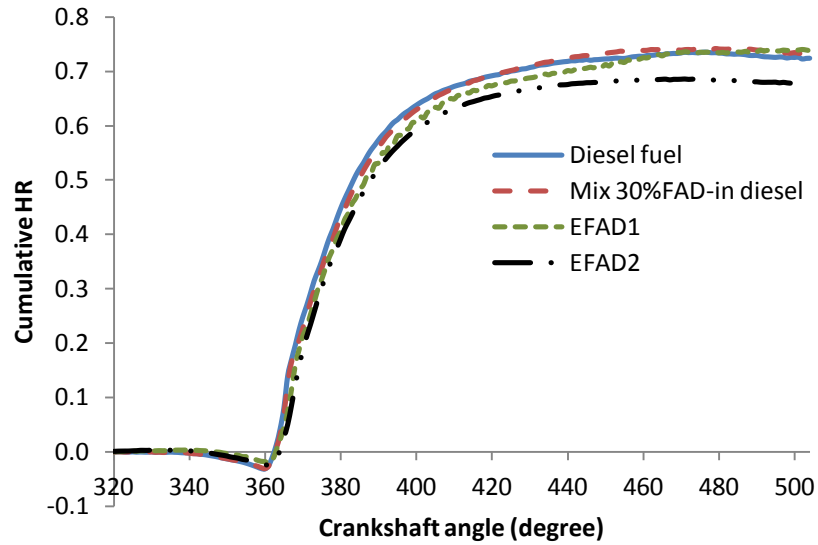
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Fig. 7. Cumulative heat release for test fuels: a)@2.36*KW*, b) @3.14*KW*, c) @3.93*KW*, d) @4,71*KW*

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3.2.4. *Variation of nitrogen oxides*

The variation of nitrogen oxides (NOx) emissions are shown in Figure 8. Significant decreases in NOx emissions for emulsified fuels compared to diesel fuel and a blend of FAD in diesel were observed. The most significant NOx reductions were registered to EFAD2 (i.e. between 10% and 26%) in comparison with diesel fuel.

As was previously mentioned, when dispersing water into fuels to make an emulsified fuel, the thermal effect of the dispersed water itself during the combustion process results in lower combustion temperature (*see temperature profile of emulsified fuels reported by Samec et al.[50]*). In agreement with Samec et al.[50], lower combustion temperature directly influences the NO formation (major contributor to NOx formation), considering the chemical reaction rate for Zeldovich mechanism. For this reason, as a consequence of the thermal effect of the water in the adiabatic flame and combustion temperature, suppression of NOx emissions for emulsified fuels are generally expected.
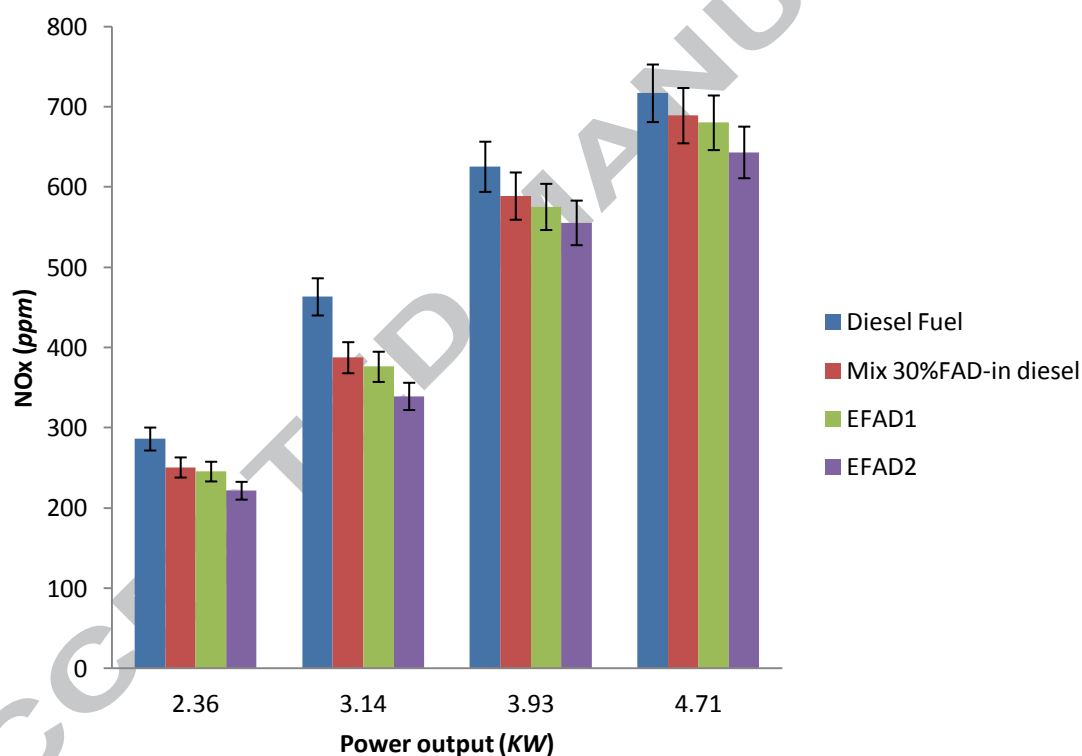

Fig. 8. Nitrogen oxides for test fuels

3.2.5. *Variation of unburned hydrocarbons*

The unburned hydrocarbons emissions (HC) are shown in Figure 9. In general, increases of the HC for emulsified fuels and a blend of FAD in diesel compared to diesel fuel were obtained with the growth of engine power output. Increases of water percentage led to increases of de HC emissions, with exception of one experiment. Although, it is valid to note that blend of FAD in diesel fuel brought higher HC emissions than emulsified fuels. Similar results for other emulsified fuels have also been reported [18, 28, 31, 46, 47, 51].

In diesel fuel combustion the main reasons for hydrocarbons (HC) emission are low temperature bulk quenching of the oxidation reactions, locally over-lean or over-rich mixture, liquid wall films for excessive spray impingement and incomplete evaporation of the fuel [52]. However, it is interesting to point out that in emulsified fuels and blend of diesel fuel in vegetable oils an important role play the viscosity, bulk modulus, density, surface tension, as well as the oxygen content.

In this investigation, the higher viscosities of the emulsified fuels and the blend of 30% FAD in diesel were achieved. This fact might affect the atomization process and lead to increases of the spray–cylinder wall interaction, which also increase the HC formation. An additional explanation might be variations in the ignition delay and the shift of the premixed combustion period (see section 3.2.2 and 3.2.3). As a result of those facts, more fuel is unburned resulting in an increase of the HC emissions.
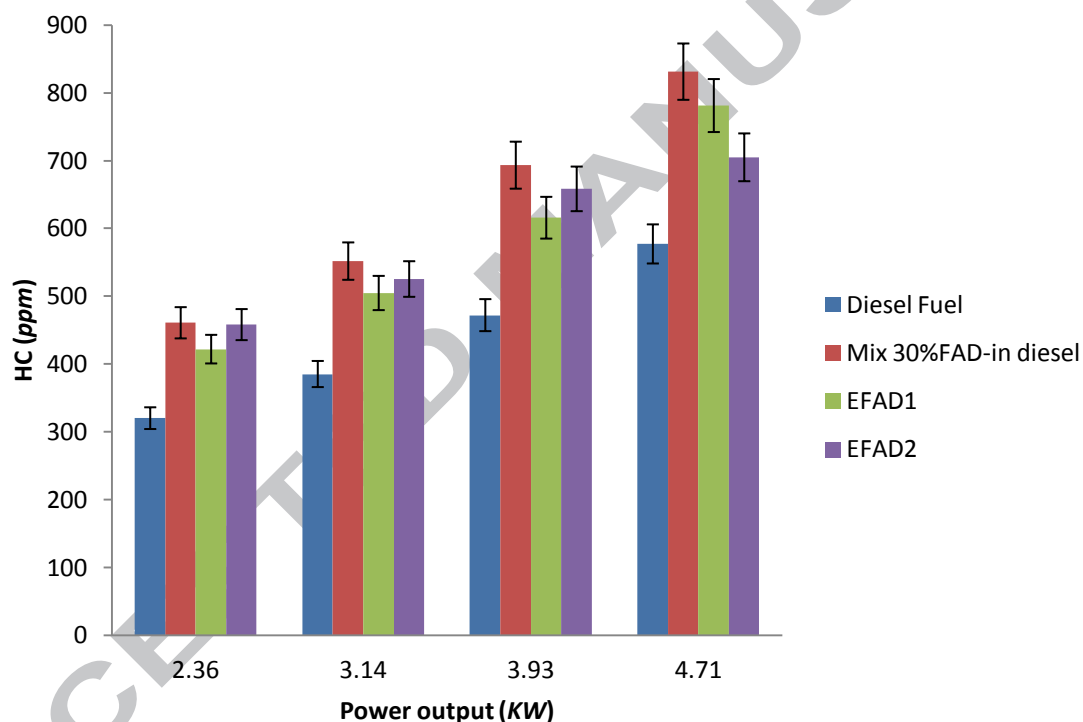

Fig. 9. Unburned hydrocarbons for test fuels

3.2.6. *Variation of carbon monoxide*

The carbon monoxide (CO) emission for test fuels is shown in Figure 10. In general, increases of the CO for emulsified fuels and a blend of FAD in diesel compared to diesel fuel were obtained. On the other hand, lower CO emissions for emulsified fuels related to blend of FAD in diesel fuel were attained. In accordance with the HC emissions, the CO emissions of emulsified fuels also increase with the increase of water percentage. The increases of CO emissions for the test fuels, manly the emulsified fuels, is a result of higher viscosity, longer ignition delays and their collateral effect on the combustion process. In agreement with results obtained in this paper, increases of CO emissions are also reported [18, 20, 21, 28, 32, 42, 47, 51, 53].

Nevertheless, in the formation process of carbon monoxide (CO) in diesel engines, factors like cylinder pressure, temperature, equivalence ratio and ignition delay and fuel spray–wall interaction play important roles [54]. Moreover, in agreement with Ithnin [55] other precursors are the incomplete fuel oxidation phenomena and the relatively slow burning of the soot (which, governed by heterogeneous kinetics, forms CO, particularly during the final phase of combustion). In addition, probably the chemical structure of the fuels (i.e. emulsions and blend) which contains oxygen in their structures, as well as the contribution of oxygen by the water and emulsifier agent also plays a decisive role. This extra oxygen in the air-fuel mixture, depending on the engine operational conditions affects the combustion efficiency.
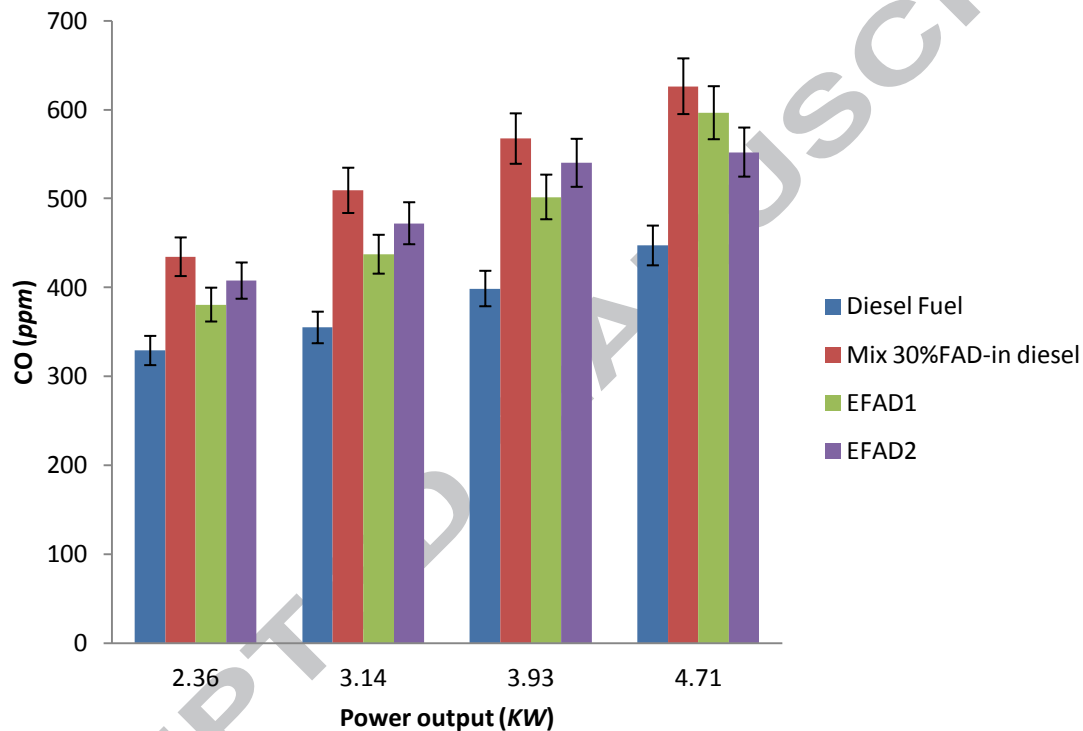

Fig. 10. Carbon monoxide for test fuels

Conclusions

The effect of emulsified fuels on a single cylinder diesel engine performance and exhaust emissions have been investigated in this research. Based on the experimental results, the following conclusions can be made:

- Several stable emulsified fuels were formulated using different diesel fuel/FAD ratio and water amount bringing stability times up to 72 hours. Based on this fact and their optical appearance all emulsified fuels were classified as emulsions. In addition, according to this physicochemical characterization, not all emulsified fuels were suitable for light duty diesel engine applications.
- In general, increases of the brake specific fuel consumption and decreases of the brake thermal efficiency for emulsions compared to diesel fuel and the blend of 30% FAD in diesel were achieved. However, at high load comparable BTE were obtained for emulsified fuels and the blend of 30% FAD in diesel.

- As result of lower cetane number and thermal effect of dispersed water into emulsified fuels, longer ignition delays for emulsions than diesel fuel and its blend in FAD were reported. However, at highest load condition no significant differences between all test fuels were achieved. These results shown that the engine works better at high load, which is an important indicative to establish that enough thermal energy for the micro-explosion is needed. On the other hand, highest late-cycle heat release rates and lowest cumulative heat release for emulsified fuels were obtained. Nevertheless, at higher power output the cumulative heat release for emulsions brought slight increases.

- The emulsification method was found as an effective way to reduce the NOx emissions. Conversely, emulsions reported increases of HC and CO emissions compared to diesel fuel. Although, it is valid to point out that blend FAD in diesel fuel brought higher HC and CO emissions than emulsified fuels. Finally, the HC and CO increases, as well as NOx emissions decrease when the water percentage was increased into emulsified fuel. Nevertheless, it is necessary to take into account that is possible to decrease the achieved emissions (HC y CO) varying some engine parameters such as injection timing and ignition delay, which might represent important improvements.

Acknowledgement

References

[1]   E. Melo, R. Piloto, R. Sierens, and S. Verhelst, "Emulsification of waste cooking oils and fatty acid distillates as diesel engine fuels: An attractive alternative," International Journal of Sustainable Energy Planning and Management, vol. 9, pp. 3-16, 2016.

[2]   B. Ping and M. Yusof, "Characteristics and properties of fatty acid distillates from palm oil," Oil Palm Bulletin vol. 59, pp. 5-11, 2009.

[3]   H. Nang, N. Wasti, and C. May. (2009, Production technology of biodiesel from palm fatty acid distillate. Malaysian Palm Oil Board. Available: http://www.palmoilworld.org/PDFs/Biodiesel/12-TT-430_Biodiesel.pdf

[4]   A. Malvade and S. Satpute, "Production of palm fatty acid distillate biodiesel and effects of its blends on performance of single cylinder diesel engine," Procedia Engineering, vol. 64, pp. 1485-1494, 2013.

[5]   S. Chongkhong, C. Tongurai, P. Chetpattananondh, and C. Bunyakan, "Biodiesel production by esterification of palm fatty acid distillate," Biomass and Bioenergy, vol. 31, pp. 563-568, 2007.

[6]   Y. Liu and L. Wang, "Biodiesel production from rapeseed deodorizer distillate in a packed column reactor," Chemical Engineering and Processing: Process Intensification, vol. 48, pp. 1152-1156, 2009.

[7]   R. Piloto, E. Melo, L. Goyos, and S. Verhelst, "Conversion of by-products from the vegetable oil industry into biodiesel and its use in internal combustion engines: a review," Brazilian Journal of Chemical Engineering, vol. 31, pp. 287 - 301, 2014.

[8]   D. Yujaroen, M. Goto, M. Sasaki, and A. Shotipruk, "Esterification of palm fatty acid distillate (PFAD) in supercritical methanol: Effect of hydrolysis on reaction reactivity," Fuel, vol. 88, pp. 2011–2016, 2009.

[9]   S. Chongkhong, C. Tongurai, and P. Chetpattananondh, "Continuous esterification for biodiesel production from palm fatty acid distillate using economical process," Renewable Energy vol. 34, pp. 1059-1063, 2009.

[10]   W. Yang, H. An, S. Chou, S. Vedharaji, R. Vallinagam, M. Balaji, et al., "Emulsion fuel with novel nano-organic additives for diesel engine application," Fuel vol. 104, pp. 726-731, 2013.

[11]   H. S. Saraee, S. Jafarmadar, H. Taghavifar, and S. J. Ashrafi, "Reduction of emissions and fuel consumption in a compression ignition engine using nanoparticles," International Journal of Environmental Science and Technology, vol. 12, pp. 2245-2252, 2015.

[12]   C. Lin and K. Wang, "Effects of an oxygenated additive on the emulsification characteristics of two- and three-phase diesel emulsions," Fuel vol. 83, pp. 507-515, 2004.

[13]   B. Prabakaran and A. Udhoji, "Experimental investigation into effects of addition of zinc oxide on performance, combustion and emission characteristics of diesel-biodiesel-ethanol blends in CI engine," Alexandria Engineering Journal, vol. 55, pp. 3355-3362, 2016.

[14]   A. Kartina and M. Suhaila, "Conversion of waste cooking oil (WCO) and palm fatty acid distillate (PFAD) to biodiesel," presented at the Sustainable Energy & Environment (ISESEE), 2011 3rd International Symposium & Exhibition in Melaka 2011.

[15]   G. Kombe, A. Temu, H. Rajabu, G. Mrema, J. Kansedo, and K. Lee, "Pre-treatment of high free fatty acids oils by chemical re-esterification for biodiesel production-a review," Advances in Chemical Engineering and Science vol. 3, pp. 242-247, 2013.

[16]   S. Chongkhong, C. Tongurai, and P. Chetpattananondh, "Continuous esterification for biodiesel production from palm fatty acid distillate using economical process," Renewable Energy, vol. 34, pp. 1059-1063, 2009.

[17]   A. Talebian-Kiakalaieh, N. Amin, A. Zarei, and H. Jaliliannosrati, "Biodiesel production from high free fatty acid waste cooking oil by solid acid catalyst," presented at the Proceedings of the 6th International Conference on Process Systems Engineering (PSE ASIA), Kuala Lumpur., 2013.

[18]   M. Mubarak and M. Senthil Kumar, "An experimental study on waste cooking oil and its emulsions as diesel engine fuel " in Advances in Engineering, Science and Management (ICAESM), Nagapattinam, Tamil Nadu 2012, pp. 61 - 66.

[19]   R. Crookes, et al., "Systematic assessment of combustion characteristics of biofuels and emulsions with water for use as diesel engine fuels," Energy Conversion and Management, vol. 38 pp. 1785-1795, 1997.

[20]   R. Crookes, et al., "Single and multi cylinder diesel-engine tests with vegetable oil emulsions," SAE Technical Paper, No. 922230, pp. 1-12, 1992.

[21]   R. Crookes, F. Kiannejad, and M. Nazha, "Seed-oil bio-fuel of low cetane number: the effect of water emulsification on diesel-engine operation and emissions," Journal of the Institute of Energy, vol. 68, pp. 142-151, 1995.

[22]   M. Ziejewski, K. Kaufman, A. Schwab, and E. Pryde, "Diesel engine evaluation of a nonionic sunflower oil-aqueous ethanol microemulsion," JAOCS, vol. 61, p. 1620−1626, 1984.

[23]   A. Schwab, M. Bagby, and B. Freedman, "Preparation and properties of diesel fuels from vegetable oils," Fuel, vol. 66, pp. 1372-1378, 1987.

[24]   C. Goering and B. Fry, "Engine durability screening test of a diesel oil/soy oil/alcohol microemulsion fuel," JAOCS, vol. 61, pp. 1627-1632, 1984.

[25]   M. Salmani, S. Rehman, K. Zaidi, and A. Hasan, "Study of ignition characteristics of microemulsion of coconut oil under off diesel engine conditions," Engineering Science and Technology, an International Journal, pp. 1-7, 2015.

[26]   T. Kibbey, L. Chen, L. Do, and D. Sabatini, "Predicting the temperature-dependent viscosity of vegetable oil/diesel reverse microemulsion fuels," Fuel, vol. 116, pp. 432-437, 2014.

[27]   M. Balcan, F. Mihailescu, D. Anghel, I. Vacaresteanu, L. Aricov, and E. Vasilescu, "Microemulsion systems containing diesel and colza oil as alternative fuels: Phase studies, interfacial tension and solubilization," Fuel, vol. 117, pp. 251-258, 2014.

[28]   D. Qi, C. Bae, Y. Feng, C. Jia, and Y. Bian, "Preparation, characterization, engine combustion and emission characteristics of rapeseed oil based hybrid fuels," Renewable Energy, vol. 60, pp. 98-106, 2013.

[29]   D. Qi, C. Bae, Y. Feng, C. Jia, and Y. Bian, "Combustion and emission characteristics of a direct injection compression ignition engine using rapeseed oil based micro-emulsions," Fuel, vol. 107, pp. 570-577, 2013.

[30]   S. Bhimani, J. Alvarado, K. Annamalai, and C. Marsh, "Emission characteristics of methanol-in-canola oil emulsions in a combustion chamber," Fuel, vol. 113, pp. 97-106, 2013.

[31]   A. Atmanli, B. Yüksel, and E. Ileri, "Experimental investigation of the effect of diesel–cotton oil–n-butanol ternary blends on phase stability, engine performance and exhaust emission parameters in a diesel engine," Fuel, vol. 109 pp. 503-511, 2013.

[32]   T. Nguyen, J. Abraham, M. Ramallo, D. Wagner, and J. McLennan, "Formulation of canola-diesel microemulsion fuels and their selective diesel engine performance," JAOCS, vol. 89, pp. 1905-1912, 2012.

[33]   C. Attaphong, L. Do, and D. Sabatini, "Vegetable oil-based microemulsions using carboxylate-based extended surfactants and their potential as an alternative renewable biofuel," Fuel, vol. 94, pp. 606-613, 2012.

[34]   D. Qi, H. Chen, R. Matthews, and Y. Bian, "Combustion and emission characteristics of ethanol–biodiesel–water micro-emulsions used in a direct injection compression ignition engine," Fuel, vol. 89, pp. 958-964, 2010.

[35]   K. Nanthagopal and R. Subbarao, "Experimental investigation and performance evaluation of DI diesel engine fueled by waste oil-diesel mixture in emulsion with water," Thermal Science, vol. 13, pp. 83-89, 2009.

[36]   L. Do, V. Singh, L. Chen, T. Kibbey, S. Gollahalli, and D. Sabatini, "Algae, Canola, or Palm Oils—Diesel Microemulsion Fuels: Phase Behaviors, Viscosity, and Combustion Properties," International Journal of Green Energy, vol. 8, pp. 748-767, 2011.

[37]   E. Melo, R. Piloto, P. Van-der-Meeren, Q. Denon, M. Balcaen, and S. Verhelst, "Emulsified fuels based on fatty acid distillates and rapeseed oil: A physicochemical characterization," Fuel, vol. 185, pp. 734–742, 2016.

[38]   Y. Sánchez, et al, "Predicción del número de cetano de biocombustibles a partir de su composición de ácidos grasos," Ingeniería Mecánica, vol. 15, pp. 147-157, 2012.

[39]   M. Ghannam and M. Selim, "Stability behavior of water-in-diesel fuel emulsion," Petroleum Science and Technology, vol. 27, pp. 396-411, 2009.

[40]   E. Melo, R. Piloto, L. Goyos, R. Sierens, and S. Verhelst, "Emulsification of animal fats and vegetable oils for their use as a diesel engine fuel: An overview," Renewable and Sustainable Energy Reviews, vol. 47, pp. 623–633, 2015.

[41]   A. Kerihuel, M. Senthil Kumar, J. Bellettre, and M. Tazerout, "Investigations on a CI Engine Using Animal Fat and Its Emulsions With Water and Methanol as Fuel," SAE Technical paper, No. 2005-01-1729, 2005.

[42]   P. Singh, J. Khurma, and A. Singh, "Coconut Oil Based Hybrid Fuels as Alternative Fuel for Diesel Engines " American Journal of Environmental Sciences, vol. 6, pp. 71-77, 2010

[43]   J. Narkpakdee, A. Permsuwan, T. Deethayat, and T. Kiatsiriroat, "Performance and emission of small diesel engine using diesel-crude palm oil-water emulsion as fuel," Energy Science and Technology, vol. 3, pp. 38-45, 2012.

[44]   G. Kannan and R. Anand, "Experimental investigation on diesel engine with diestrol-water micro emulsions," Energy, vol. 36, pp. 1680-1687, 2011.

[45]   D. Ogunkoya, S. Li, O. Rojas, and T. Fang, "Performance, combustion, and emissions in a diesel engine operated with fuel-in-water emulsions based on lignin," Applied Energy, vol. 154, pp. 851-861, 2015.

[46]   N. Rao, B. Sudheer, and M. Yohan, "Performance and emission characteristics of straight vegetable oil-ethanol emulsion in a compression ignition engine," ARPN Journal of Engineering and Applied Sciences, vol. 7, pp. 447-452, 2012.

[47]   N. Rao, B. Sudheer, and M. Yohan, "Study of Different Methods of Using Vegetable Oil as a Fuel for Compression Ignition Engine," Global Journal of Researches in Engineering (A), vol. 12, pp. 9-16, 2012.

[48]   J. Heywood, Internal Combustion Engine Fundamentals. New York: Mc Graw-Hill., 1988.

[49]   A. Alagumalai, "Combustion characteristics of lemongrass (Cymbopogon flexuosus) oil in a partial premixed charge compression ignition engine," Alexandria Engineering Journal, vol. 54, pp. 405–413, 2015.

[50]   N. Samec, B. Kegl, and R. Dibble, "Numerical and experimental study of water/oil emulsified fuel combustion in a diesel engine," Fuel, vol. 81, pp. 2035-2044, 2002.

[51]   M. Senthil Kumar and M. Jaikumar, "A comprehensive study on performance, emission and combustion behavior of a compression ignition engine fuelled with WCO (waste cooking oil) emulsion as fuel," Journal of the Energy Institute, vol. 87, pp. 263–271, 2014.

[52]   S. Imtenan, M. Varman, H. Masjuki, M. Kalam, H. Sajjad, M. Arbab, et al., "Impact of low temperature combustion attaining strategies on diesel engine emissions for diesel and biodiesels: A review," Energy Conversion and Management, vol. 80, pp. 329-356, 2014.

[53]   R. Crookes and F. Kiannejad, "Diesel Engine Operation with Vegetable Oil - Alcohol Emulsion," Elaeis—Special Issue: Proceedings 1995 PORIM International Biofuel Conference, pp. 42-49, 1995.

[54]   M. Fahd, Y. Wenming, P. Lee, S. Chou, and C. Yap, "Experimental investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition," Applied Energy, vol. 102, pp. 1042-1049, 2013.

[55]   A. Ithnin, M. Ahmad, M. Bakar, and S. Rajoo, "Combustion performance and emission analysis of diesel engine fuelled with water-in-diesel emulsion fuel made from low-grade diesel fuel," Energy Conversion and Management, vol. 90, pp. 375-382, 2015.

HIGHLIGHTS

Discussion of various issues with regard to formulation of emulsions containing FAD

Stable emulsions were produced using FAD, diesel fuel and a mixture of surfactants

The effect of emulsions on engine performance and exhaust emissions were studied

Emulsions containing FAD and water lead to higher BSFC and delayed start of combustion

Emulsions were found as an effective way to reduce the nitrogen oxides emissions