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Original article

An investigation of performance and emission characteristic of a small marine engine running on heated coconut oil and diesel oil

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Abstract

In recent years, much interest has been devoted to bio-fuels because of their beneficial effects on environment, agriculture and economic development. Raw vegetable oil – a kind of bio-fuels, still exits many downsides, is potential renewable fuel replaced for ever-exhausted fossil fuel. In this report, vegetable oil which is available in the South of Vietnam such as raw coconut oil is studied by heating up different temperature with the aim at decreasing its high viscosity and density and meeting the fuel requirements. The experiments are conducted on heated coconut oil (HCO) and fossil diesel oil (DO) using an 80hp of small marine diesel engine. The results of engine performance as using DO and HCO included engine power (N_e), specific fuel consumption (SFC), thermal efficiency (TE), emission characteristics such as carbon monoxide (CO), unburned hydrocarbon (HC), smoke, nitrogen oxides (NO_x) at internal feature are measured. The experiment results show higher SFC, CO, HC and smoke emissions, and lower TE, and NO_x emissions for HCO with respect to DO. In addition, this study also reveals that, 100^0C of HCO is said to be the most suitable heating temperature as getting the engine performance equals to DO.

Keywords: bio-oil, bio-fuels, emission characteristic, engine performance, small marine engines

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1. Introduction

It is necessary to base alternatives fuels on the criterions such as availability, low cost, advantage for environment, meeting the demand of people on energy, ensuring food security without losing the engine performance. In developing nations, crises and depletion of fossil fuel, environmental protection always play a crucial part in using fuels for internal combustion engines. Nowadays, reducing the greenhouse gases and rising the clean development of global has contributed to promote the consumption of bio-fuels such as bio-alcohol, vegetable oils, biomass, biogas, biodiesel, dimethyl ether. This has become a broad issue to the general public (Hoang, 2017). However, fossil fuel can be replaced by such bio-fuels, while it is compulsory for others to improve their properties in order to bring the similar properties to traditional fuels (Tran, et al., 2018). Especially, there are many researches that aimed at using vegetable oils or animal fat and the converted the product based on vegetable oils (VOs) or animal fats (AFs) into potential and easy-using alternative fuels for diesel engines (Hoang, et al., 2018).

In the South of Vietnam, there are many abundant rural products such as sunflower oil, peanut oil, rubber seed oil, coconut oil, jatropha oil and catfish fat. These oils can be taken to use as in-diesel engine fuels. Some people living in rural areas have used coconut oil or catfish fat for small fishing vessels in the South and used jatropha oil or for generator diesel engines in the Middle. Therefore, using VOs as fuel for diesel engine has many advantages such as sustainability, rural development, reducing in toxic emissions (Hoang, 2017). However, raw vegetable oils' high viscosity, density and surface tension may lead to the poor atomization, lower evaporation, heterogeneous mixture and resulting in inferior of diesel engine power and emission. Many researchers have shown the method for minimizing the drawbacks of vegetable oils such as:

Transesterification to biodiesel

Biodiesels are expected to consider as transesterification products after moving glycerol from bio-oils, which include VOs or AFs. The biodiesel was named and described its applicability for diesel engines (Demirbaş, 2002). Lower pollution and renewable sources were interested as applying on diesel engines to replace fossil fuel have been considered as main benefits of biodiesel (Manjunath et al., 2015). Using catalysts in the reaction between VOs or AFs and methanol, 2-propanol, ethanol, and butanol has carried out for transesterification, that is potential and cheap of transforming bio-oils with the large structure and non-straight-chain molecules into smaller structure, straight-chain molecules meet the requirement of fuel standard for diesel engines (Hoang, 2018). The biodiesel properties such as viscosity, cloud point, heat of combustion, volatility are similar to diesel oil, density, and especially cetane number of biodiesel are much higher than that of fossil diesel oil. Besides, people are encouraged to use biodiesel as fuel more than fossil fuel because of its biodegradability, no sulfur and aromatic content (Panwar et al., 2011).

Emulsion with low viscosity liquid

Emulsion of two fluids, which are non-miscible, is a steady dispersion that continuously produces a droplets phase and reduces the surface tension, maximizes the contact areas to make emulsions (Agarwal et al., 2017). One of experimental surveys on using palm oil emulsions for a diesel engine shown that unburn hydrocarbon (HCs), carbon monoxide (CO), and carbon dioxide (CO_2) emissions of emulsions between palm oil and water are more favourable than that of diesel oil and it reduces wear of the moving parts (Mosarof et al., 2015). Moreover, Anbarasu and Karthikeyan, (2016) conducted experience on diesel engines using diesel oil with the emulsions of rapeseed oil and 10% of water by volume. The obtained results are reported about the increase in engine thermal efficiency, meanwhile emissions of smoke and NO_x were decreased significantly (Hoang and Nguyen, 2017). These results are given while using the emulsion of vegetable oil-water that is obtained via ultrasonic (Burton et al., 2014). Furthermore, the emulsions of honge oil with ethanol and butanol such as ESVO-80 and ESVO-70 has been tested for an engine(Rao et al., 2012). The obtained data showed that, viscosity was lower, volatility was improved, combustion was better and carbon deposits were less.

Blends with fossil fuel

Vegetable oils are diluted with fossil fuel in order to reduce viscosity and increase cetane number. Ganjehkaviri et al., (2016) carried out an experimental test for a diesel engine using VO in comparison with its blends with fossil diesel oil in case the volume of VO is changed in the range of 25%, 50%, and 75%. The results showed that, when engine used vegetable oil blends, fuel consumption equaled to fossil diesel oil but NOx emission was lower than the case of using fossil diesel oil (Hoang, et al., 2018). Furthermore, a diesel engine performance and emission characteristics while fueled with 20%, 40%, 60% of palm oil blends with diesel oil were evaluated and determined by Iqbal et al., 2013. The tests also showed that in case of using blends of a small percentage of palm oil in comparison with diesel oil, the same thermal efficiency and low emission were observed.

Hydrotreated vegetable oil (HVO)

A well-known fully potential alternative fuel is HVO due toits high cetane number, no sulphur and aromatic content. HVO is proved as the same as the fuels, which is produced by using Fischer-Tropsch (FT) synthesis (Chau et al., 2017). HVO derived from bio-oil sources is considered as long straight-chain paraffin (n-paraffin) and non-straight-chain (iso-paraffin) like petro-diesel oils (Walther et al., 2012), where converted double bonds to hydrocarbons by saturating is occurred whereas oxygen content is moved by the decarboxylation or decarboxylation reaction to produce $C_{17}H_{36}$, and dehydration to produce $C_{18}H_{38}$(Hoang and Van Le, 2017). Overall, the storage stability of new paraffinic fuels is better and more accepted easily by fuel distributors, engine designers and manufacturers than biodiesels. Nevertheless, the absence of sulfur is the main cause of low lubricity (Jaroonjitsathian et al., 2014) but similar methods are applied to HVO to improve the lubricity of ultra-low sulphur fossil fuel(Vojtisek-Lom et al., 2017).

Preheated vegetable oils

Dramatically reducing the cost of vegetable oils due to bypassing the converting of bio-oils into biodiesel has increased the potential of VOs. However, the disadvantage of VOs is their high viscosity property. Because of the current engine design for low viscosity fuel, VOs cause deposit residues on the injectors. Therefore, heating method for vegetable oils is proposed in order to avoid the above condition. As an example, Sivalakshmi and Balusamy, (2011) used palm oil and rapeseed oil as alternative fuel for a diesel engine, and came to the conclusion that the test engine performance was acceptable but only in short time of operation in case of using palm oil. However, this oil caused deposits on piston head and cylinder, sticking of piston rings if operations in long time. Heated neat jatropha and kharanja oils has been used for a test engine by Astrup et at.(Astrup et al., 2015). Their viscosity’s reduction is about 80-90 % while be preheated to 90°C and at this temperature, their properties are equal to diesel oil. Preheated raw rapeseed oil (RRO) to 100^{o}C was considered as fuel by Hazar and Aydin, (2010). They shown that the preheated vegetable oils affected positively the engine power and emissions. The filter-clogging problem is solved by preheating vegetable oils before injection (Corsini et al., 2015).

This work uses heating method to improve the drawback of vegetable oil because it is a simple method with high applicability. If vegetable oils, especially inedible oils, are used for diesel engines, it will reduce the environmental pollution and increase the self-provided-fuel for domestic waterway transportation means, generator or agriculture machine in Mekong Delta, South, Vietnam.

2. Materials and methods

2.1. Materials

Among the plants provide vegetable oils and seed oils can be grown in Vietnam, coconut, jatropha, soybean, rubber and peanut trees are considered as favorite ones. However, the coconut trees are planted primarily in the Southern areas in Vietnam and several countries in Southeast Asia. Coconut trees are widely planted in the tropics, along the coast and in the islands of 90 countries, with more than 11 million hectares, mostly concentrated in the Asia Pacific. Ten countries with the largest area of growing coconut in the world are Indonesia, Philippines, India, Sri Lanka, Brazil, Thailand, Papua New Guinea, Malaysia, Vietnam, and Vanuatu. Three of them for leading are Indonesia, Philippines, India where have more than 1 million hectares of growing coconut trees and get over 80% of quantity in the world. However, coconut productivity of the countries such as India, Sri Lanka, and Vietnam has much higher than that of others. Productivity of coconut fruits per a hectare in a year of Vietnam is denoted in Table 1 and rate of productivity in comparison with other countries in the world is shown in Figure 1.

Table 1: Area and productivity of coconut in some countries

Countries	Area (hectare)	Productivity (fruits/hectare /year)
Indonesia	3.800.000	4.000
Philippines	3.560.000	3.719
India	1.900.000	7.748
Srilanka	395.000	7.346
Thailand	247.000	4.800
Vietnam	144.800	8.294

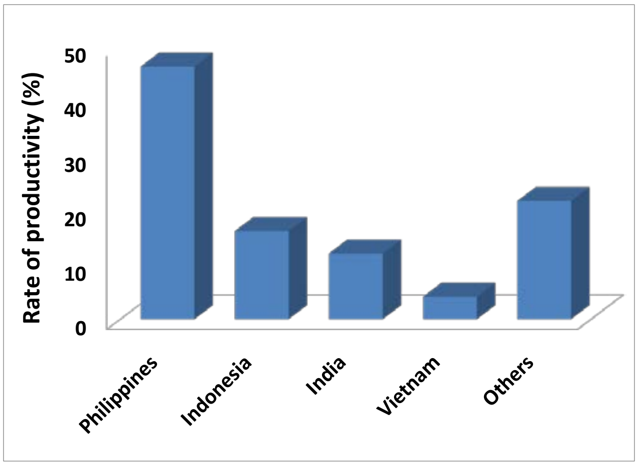

Figure 1: Rate productivity of coconut in the world

Table 1 and Figure 1show that, although Vietnam is the sixth country about the area of growing coconut trees but Vietnam is the fourth of the productivity. Therefore, Vietnam is a country with huge potential of the coconut oil sources. Hence, if coconut oil is used as fuel, it will not only create the source of alternative fuel, reduce the dependence on fossil fuel but also decrease the toxic emissions. Based on the potential of coconut oil sources, this work uses heated raw coconut oil for a diesel engine for evaluating engine performance and emissions. The coconut oil properties at 30^{o}C in comparison with fossil diesel oil are given in Table 2.

Table 2:Coconut oil and diesel oil properties at 30^{o}C

Fuel	ASTM standards	Coconut oil	Diesel oil
Higher heating value (MJ/kg)	D240	40	45
Kinematic viscosity, (cSt)	D445	31	4.0
Surface tension, (mN/m)	D971	34	26
Density, (g/cm^3)	D1298	0.91	0.85
Cetane number	D613	40	46
Flash point, (^{o}C)	D93	200	68
Cloud point, (^{o}C)	D 97	21	-7
Distillation temperature 90% vl, ^{o}C	D 86	360	362
Copper plate corrosion	D 130	1	1
Carbon (weight percent)	D5291	75.4	83.5 - 87
Hydrogen (weight percent)	D5291	11.8	11.5 - 14
Oxygen (weight percent)	D5291	11.6	0
Sulfur (in % weight levels)	D4294	0.01	0.02 – 0.05

It can be seen from Table 2 that, some advantages of coconut oil as fuel are containing oxygen function in molecular and does not contain non sulphur. However, its density, surfacetension and kinematic viscosity at low temperature are much higher and cetane number of coconut oil is lower than that of diesel oil. Actually, the atomization, and mixture are primarily affected by fuel surface tension and kinematic viscosity. Poor atomization and mixture will result in the incomplete combustion, increasing the toxic emission and exhaust gas temperature. Thus, three parameters including density, kinematic viscosity, surface tension are most important. However, the disadvantages of coconut oil can be improved by the simplest method - heating method.

2.2. Methods

To evaluate and determine the most suitable temperature for heating coconut oil based on viscosity, density and surface tension as a function of temperature, some procedures was used. The ASTM D1298 standard with an accuracy of three decimals for measuring density, the ASTM D 445 standard with an accuracy of 0.02cst and 0.0359 of viscometer constants for measuring kinematic viscosity, Du Nouy ring method with a tension meter based on the ASTM D971 standard for measuring surface tension were used. The above indicators of coconut oil were determined in range of 40^{o}C to 120^{o}C and repeated three times to take the average value. The relationship between coconut oil physical properties and temperature are plotted in Figure 2, Figure 3, and

Figure 4.

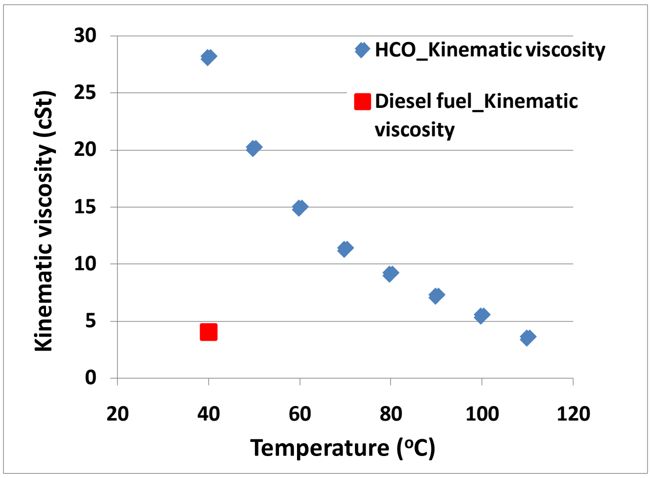

Figure 2: Raw coconut oil kinematic viscosity as a function of temperature

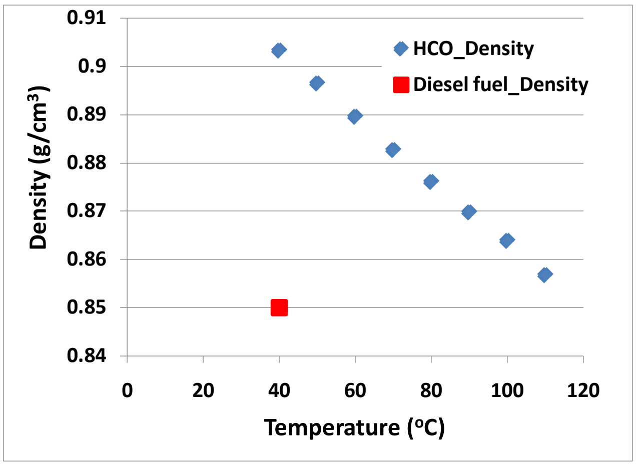

Figure 3: Raw coconut oil density as a function of temperature

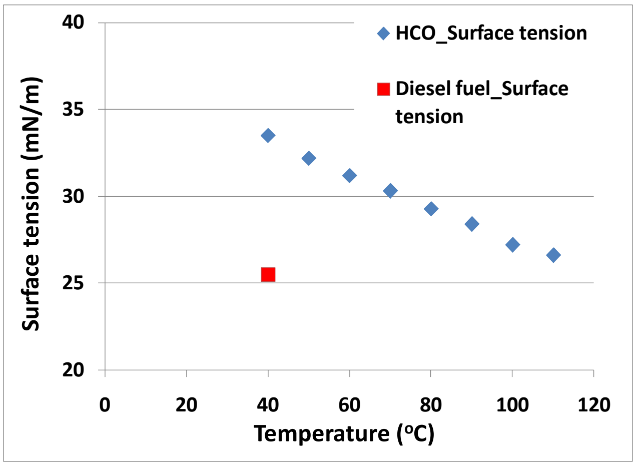

Figure 4: Raw coconut oil surface tension as a function of temperature

It can be observed from Figure 2, Figure 3 and Figure 4 that, viscosity of coconut oil is similar to, although surface tension is 2 mN/m higher and density is 0.013 g/cm^3 higher than those of diesel oil's at 100°C. These values of coconut oil are much higher in comparison with diesel oil at 80°C. However, at 120°C, the reduction in viscosity, density, surface tension needs to beconsidered. Therefore, heated coconut oil at 80°C (HCO_t80), 100°C (HCO_t100) and 120°C (HCO_t120) are used for this experiment in order to determine the effect of fuel heating temperature on test engine performance and emission characteristics.

3. Experimental setup

In this study, the experiment with a test diesel engine to evaluate the engine performance and emission characteristic is carried out on test-bed at IC Engine Key Lab. The D243 diesel engine with 80hp of power, which may be installed on the small ships or vessels with tonnage of about 100 tons that are available in the South, Vietnam, is considered as testing object and described in Table 3.This ships or vessels kind are usually used for inland waterway transportation.

Table 3: Specifications of D243 diesel engine

Type	Vertical, 4-stroke, 4 cylinders, direct injection, cooled by water, compression ignition
Model	D243 from Belarus
Rated Power	80 HP at 2000 rpm
Maximum speed	2200 rpm
Bore/ Stroke	110/125 mm
Compression ratio	16.7:1

This test engine is fuelled with heated raw coconut oil HCO_t80, HCO_t100, and HCO_t120 respectively and diesel oil (DO) at different load with internal feature at 1500 rpm of speed. During experiments, the test engine is provided fully with lubricant and cooling aiming at maintaining the test diesel engine stability. The provided fuel rate with the D243 engine is determined versus the measurement device, and electronic sensor. The fuels for each measurement are repeated three times to aim at reaching the highly exact average results. The diagram of setting up the experiment on engine test-bed is shown in Figure 5.

The function of cluster brake is to work as generator and engine mode, therefore it can be used to make the experiments on the engine test-bed. Cabinets CEB-II is a system containing the modules such as blocks of heating (HSU), diagnostic and control for analyzing accurately the exhaust components include carbon monoxide and dioxide (CO and CO$_2$), nitrogen oxides (NO and NO$_x$), hydrocarbons (HC) accuracy and smoke. This CEB-II analyzer is also installed with computer fitted GEM110 software, and it is done via digital signal. The parameters of analyzer accuracy are given in Table 4.

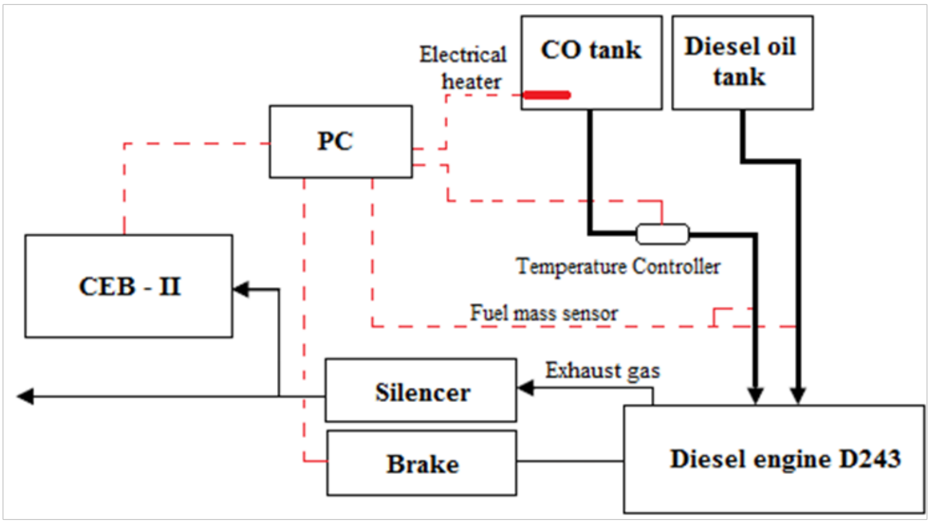

Figure 5: Experimental setup on D243 test-bed

Table 4: Emission measuring range and accuracy of analyzer

Device	Parameters	Measuring range	Accuracy
Exhaust gas analyzer	Carbon monoxide (CO)	0 – 10.000 ppm	2 ppm
	Hydrocarbon (HC)	0 – 20.000 ppm	5 ppm
	Nitrogen oxide (NO_x)	0 – 5000 ppm	1 ppm
Smoke meter	Smoke	0 – 99.8%	0.2%

4. Results and discussion

4.1. Engine performance

The engine performance with heated coconut oil was determined and evaluated about engine power (N_e), specific fuel consumption (SFC), thermal efficiency (TE) at different load of the engine.

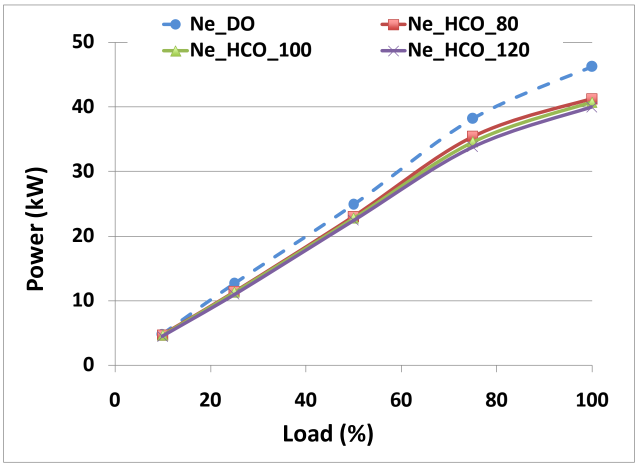

Figure 6: Relationship between (Ne) and engine load

In the case of using HCO as fuel, smaller lower heating value and cetane number is primary cause to lead to reduction in engine power even HCO is injected at 80°C -120^{o}C aiming at decreasing viscosity, increasing the vaporization rate, mixture, and combustion. In Figure 6, for only HCO, engine power of HCO_t80 is higher than that of HCO_t100 and HCO_t120, it is explained due to HCO_t80 density is larger, hence the fuel mass is larger as well as the energy content at constant volume of injected fuel into the cylinder. However, in comparison with DO, engine power as using HCO decreases 8.49%-13.45%. HCO with larger viscosity, density and surface tension may result in a poor atomization, vaporization, and nebulisation, especially at low load and regimes in which the temperature in combustion chamber is low. In fact, the injection time and quality play an important part in at conditions of operation such low load and regimes because the injected fuel amount is small. Moreover, injection time is separated to three main period phases: a first period phase is considered as the opening of injectors, at second period phase is the main one, and the last is the closing period phase. As the total time of injection process is small, it means, the first period phase and last period phase is also small. Thus, the worst atomization, vaporization, and nebulisation along with lower cetane number are the consequence cause bad combustion that in turn leads to an engine power loss.

The SFCs of a test diesel engine operated at different load and fueled with different HCO compared to DO is presented in Figure 7 that can be seen that, SFCs are proportional inversely to the engine load. However, at higher loads, SFCs increases. These results may explain that increase in fuel mass in comparison with same-obtained-power in test time, besides the heat losses of engine run at higher loads is less than that of lower loads. The SFC for HCO_t80, HCO_t100 and HCO_t120 is higher than that of DO by 42.66%, 36.17%, 41.04%, respectively. If the SFCs of HCO is calculated about weight, it is observed due to higher densities of HCO resulted in higher weight for SFC. Because the density of HCO_t80 is 2.98% higher, the density of HCO_t100 is 2.27% higher. Moreover, the higher densities of HCO_t80, HCO_t100 result in higher mass of injection although at the same fuel volume and injection pressure, otherwise HCO cetane number and heat content are lower than those of DO. However, although the density of HCO_t120 is slightly lower than that of DO but the obtained power from HCO_t120 is also lower in comparison with in case of using HCO_t80 and HCO_t100 Therefore, the fuel consumption volume is 2.98% higher for HCO_t80, is 2.27% for HCO_t100. Maximum SFC of HCO_t80 is 620.13 g/kW.h, of HCO_t100 is 596.08 g/kW.h, HCO_t120 is 608.21 g/kW.h in comparison with 533.75 g/kW.h of DO. Similar results are also shown and presented by some researches (Hoang et al., 2017; Singh, 2013).

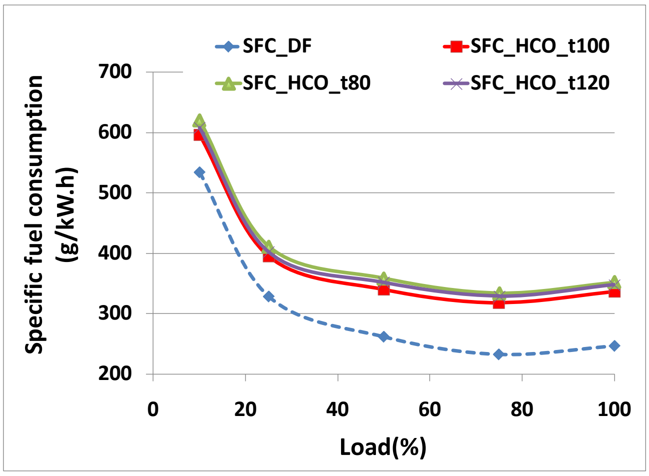

Figure 7: Relationship between SFC and engine load

The thermal efficiency (TE) of a diesel engine is calculated as:

$$TF = \frac{N_e}{Q} = \frac{3600}{(SFC)(LHV)} \quad (1)$$

Where Q (kW) is achieved energy with supplied fuel mass; LHV (MJ/kg) is lower heating value.

The thermal efficiency of test engine considered as a function of engine load while fueled with different fuels is plotted in Figure 8. The maximum thermal efficiency is 29.57% for HCO_t80, 31.06% for HCO_t100 and 30.02% for HCO_t80 as compared to 38.73% for diesel. This may be understood due to the cetane number and heating value of HCO are lower than those of DO. At lower loads, thermal efficiency trend of all test fuels increase but decrease while engine run at high loads. Maximum variation thermal efficiency is23.64% of HCO_t80, 19.80% of HCO_t100 and22.48% of HCO_t120 lower than that of DO.

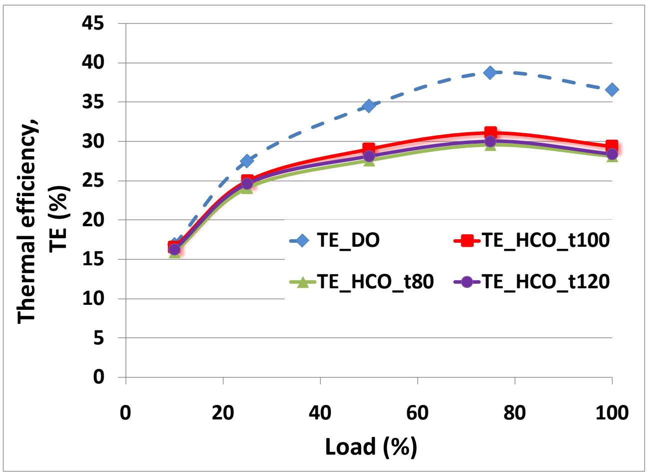

Figure 8: Relationship between TE and engine load

4.2. Engine emissions

The carbon monoxide emission(CO) and hydrocarbon emission(HC) features of test engine fueled with HCO and DO are shown in Figure 9 and Figure 10.

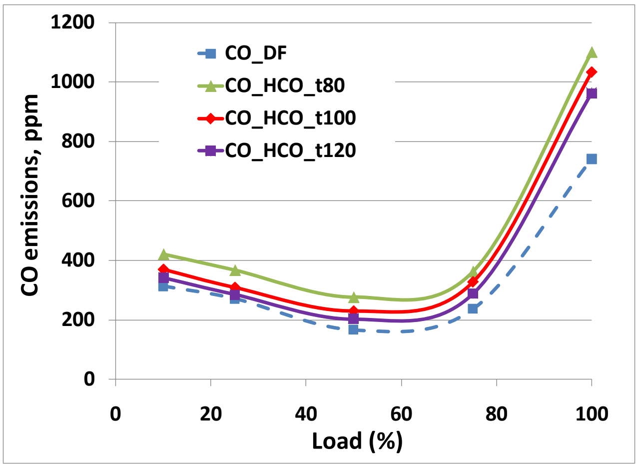

Figure 9: Relationship between carbon monoxide emission and engine load

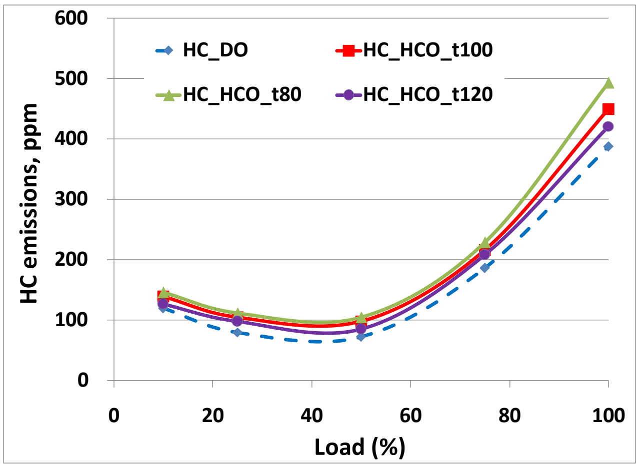

Figure 10: Relationship between hydrocarbon emission and engine load

Test engine are conducted and determined the emission characteristics using HCO and DO. Higher TE and lower SFC for DO in comparison with lower TE and higher SFC for HCO are observed in Figure 7 and Figure 8. TE of HCO_t80 is lowest but SFC of HCO_t80 is highest. Lower calorific value of coconut oil may be the main cause results in being necessary to increase the fuel volume aiming at maintaining the same input energy as in case of using DO to the engine. This reason is explained due to high kinematic viscosity, density and surface tension of HCO_t80, which result in poor atomization, low evaporation because of larger fuel surface energy and droplets and it is inadequate mixture of coconut oil and compressed air. For HCO_t120, due to lower kinematic viscosity (1.2 cst) therefore ultra-dilution fuel may strongly affect the injection and this is the cause leads to the reduce in TE but increase in SFC compared to HCO_t100. However, TE of HCO_t100 is higher, otherwise SFC is lower than those of HCO_t80 and HCO_t120 but is not so equal as DO's. The primary reason may be the improved fuel atomization, evaporation, mixture up to the most suitable value of viscosity and surface tension.

The CO emissions with HCO and DO at changing loads of engine are compared in Figure 9. The CO emissions are not much different from these fuels at lower loads, but at higher loads, CO emissions from HCO are higher than that of DO. The CO eliminated from HCO_t80 is 420 – 1101 ppm higher, from HCO_t100 is 370 – 1034 ppm higher, from HCO_t120 is 341 – 962 ppm higher in comparison with 312 – 740 ppm of DO. With average results, CO produced from HCO_t80 is 47.71% higher, from HCO_t100 is 29.80% higher, from HCO_t120 is 17.76% higher than that of DO. It can be observed from Figure 10, similar to CO emissions, the HC released from HCO_t80 is 104 – 493 ppm higher, from HCO_t100 is 98 – 449 ppm higher, from HCO_t120 is 84 – 421 ppm higher in comparison with 72 – 387 ppm of DO. With average results, CO discharged from HCO_t80 is 28.43% higher, from HCO_t100 is 19.26% higher, from HCO_t120 is 11.10% higher than that of DO. This occurs due to at lower load, the temperature of cylinder is low. Therefore, fuel combustion is more difficult. At higher temperature, engine performance is improved, however while further loading, the supplied fuel is excess the required fuel mass resulting in forming more smoke. This leads to be lack of oxygen and prevent from converting CO to CO_2 and burning perfectly fuel therefore the CO, HC emissions dramatically increase. Produced smoke and NO_x emission characteristics of test engine using DO and HCO as function of load are presented in Figure 11 and Figure 12, respectively.

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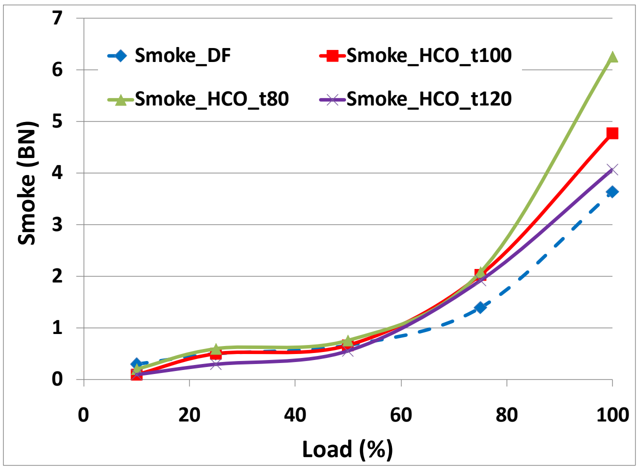

Figure 11: Relationship between smoke emission and engine load

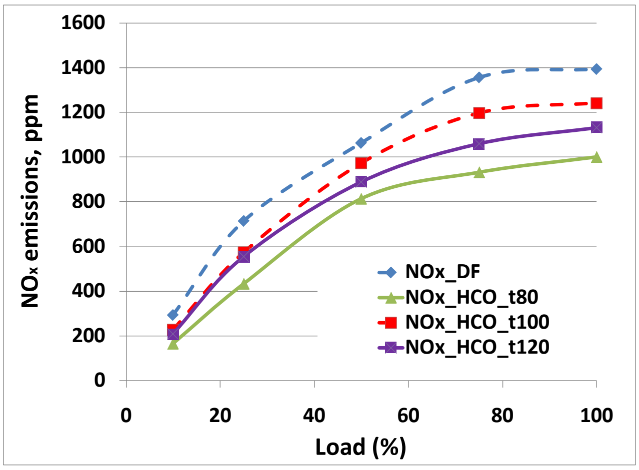

Figure 12: Relationship between NO$_x$ emissions and engine load

Smoke is also one of the results about incomplete and imperfect combustion of HCO. Especially, fuel is injected more into the combustion chamber and massive molecules at higher loads, higher surface tension and viscosity of HCO leading to lower evaporation, poor atomization. Figure 11 demonstrates that, at lower loads, the smoke emission of HCO is lower than that of DO. This may be due to the oxygen presence in molecular of coconut oil compared with DO and coconut oil is injected with a small mass so it is burnt more completely. However, at higher loads, larger coconut oil mass is injected into combustion chamber and incomplete combustion leads to increase in smoke emission. For HCO, the lowest smoke opacity is observed with HCO_t120. The average smoke opacity is increased by 24.12%, 0.38% for HCO_t80, HCO_t100, respectively but decreased by 14.82% for HCO_t120.

Thereafter, Figure 12 shows that, the fueling HCO_t100 increases NO$_x$ emissions in comparison with HCO_t80 and HCO_t120. This increase in NOx emissions for HCO_t100 may be due to HCO_t100 physical properties is the closest to DO's although oxygen content in an atom and cetane number are unchanged. However, the injection rate, spay characteristics, heating value and cetane number are the interacting factors that exert an effect on combustion of fuel. Therefore, the consonance of above factors results in increasing the NOx emissions for HCO_t100 in comparison with HCO_t80 and HCO_t120. The more engine load increases, the more the NOx emissions increase. With average results, the NOx emissions of HCO_t100 is 14.63% lower than that of DO but 21.97% and 8.14% higher than that of HCO_t80 and HCO_t120, respectively.

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