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EFFECT OF A HOMOGENEOUS COMBUSTION CATALYST ON COMBUSTION CHARATERISTICS AND FUEL EFFICIECNY OF BIODIESEL IN A DIESEL ENGINE

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ABSTRACT

The purpose of the present study is to investigate the impact of a ferrous picrate based homogeneous combustion catalyst on the combustion characteristics and fuel efficiency of a biodiesel in a diesel engine. The experimental work was conducted using a naturally aspirated, four-stroke, single cylinder direct injection diesel engine at a constant speed of 3200rpm under various load conditions. A ferrous picrate based catalyst was added into the biodiesel at a dosing ratio of 1:10000 by volume. It was found that the biodiesel had higher brake specific fuel consumption and lower brake thermal efficiency, relative to a commercial petroleum-derived diesel. The ignition delay time was shorter for the biodiesel than the petroleum diesel with the difference increasing with increasing engine load. The in-cylinder pressure and heat release analysis revealed that the biodiesel had a higher maximum cylinder pressure and longer combustion duration compared to that of the diesel. The application of the ferrous picrate based catalyst in the biodiesel resulted in lower brake specific fuel consumption and higher brake thermal efficiency. Up to 2.8% fuel saving was observed with the use of the catalyst in the biodiesel under the tested conditions. It was found that the catalyst reduced the ignition delay time and combustion duration of the biodiesel in the engine, which resulted in a slightly higher peak cylinder pressure and faster heat release rate.

Keywords: biodiesel, combustion characteristics, diesel engine, fuel efficiency, homogeneous combustion catalysts

1. INTRODUCTION

Compression ignition engines, also known as diesel engines, are widely used in the heavy machineries, mining equipments and road transportation powered by diesel fuel due to their relatively higher thermal efficiency and greater power output [1]. However, diesel engines produce heavy emissions, particularly particle matters (PM) and NOx [2]. Due to the ever increasing fuel price, limited fuel supply and the more stringent emission regulations imposed by governments around the world, a number of new technologies have been proposed to improve the fuel efficiency and reduce engine emissions.

Biodiesel, which is converted from the vegetable oil or animal tallow, has been promoted by its proponents as an alternative fuel to conventional petroleum derived diesel [3-5]. The claimed benefits of using biodiesel in diesel engines include lower smoke, unburned hydrocarbon and carbon monoxide emissions due to the presence of oxygen in biodiesel [6, 7]. However, many studies have reported that the use of biodiesel often resulted in higher NOx emission and lower fuel efficiency [6]. This is mainly due to the differences in the chemical structure and physical properties between diesel and biodiesel, which lead to a different combustion characteristics (i.e., ignition delay time, peak flame temperature and combustion duration) of biodiesel in diesel engines. In general, it is reported that biodiesel has a shorter ignition delay relative to petroleum diesel. However, the reported data on the combustion duration were not consistent. Many studies reported longer combustion durations of biodiesel than that of diesel [7, 8] while others observed an opposite trend [9].

It was found that the engine performance fuelled with biodiesel could be improved using metal-based combustion catalysts [10-12]. These catalysts are dissolved into diesel or biodiesel homogeneously to play a catalytic role during combustion process within the engines. A number of metal ions have been found to promote hydrocarbon combustion such as Iron [13, 14], Cerium [15], Platinum [16], Copper [17], and Manganese [11]. These metal-based homogeneous combustion catalysts have been found to be capable of achieving higher fuel efficiency and lower engine emissions. The improvements in fuel efficiency and emission reductions are significant as summarised in Table 1. The effects of metal-based homogeneous combustion catalysts on the performance of biodiesel fuelled diesel engines have also been reported. Sajith et al [12] investigated the influence of a cerium based catalyst on major physicochemical properties of biodiesel and engine performance. It was found that the use of the catalyst increased the flash point and viscosity of biodiesel. It was also found that the brake thermal efficiency was improved up to 1.5% and unburned hydrocarbon was reduced up to 40% with the application of the catalyst in the biodiesel. Keskin et al [11] found that Mn and Ni based catalysts improved the pour point and viscosity of biodiesel while decreased the specific fuel consumption and emissions of CO, NOx and smoke. Kannan et al [10] investigated the effect of ferric chloride, as a homogeneous combustion catalyst, on the engine performance fuelled with biodiesel in terms of engine efficiency and emissions. It was found that the brake thermal efficiency was increased by 6.3% while CO, HC and smoke was reduced by 52.6%, 26.6% and 6.9%, respectively. It was also found that the use of the catalyst slightly lowered NOx emission.

A series of studies into a ferrous picrate based homogeneous combustion catalyst has been conducted in the authors' laboratories. The composition of the catalyst is a ferrous picrate-water-butanol solution with additives [13]. These additives are mainly short-chain alkyl benzene and its derivatives, which help improve the stability of the ferrous picrate-water-butanol-diesel mixture. Based on laboratory tests on a small diesel engine [13, 14], the brake specific fuel consumption was reduced by up to 4% and the smoke emission was reduced up to 40% with the addition of the catalyst in petroleum diesel. However, the use of this catalyst on the performance of biodiesel has not been studied yet.

The objective of the present study is to investigate the effect of the ferrous picrate based homogeneous combustion catalyst on the fuel efficiency and combustion characteristics of a biodiesel fuel in a diesel engine under various operating conditions.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1 Experimental Materials

A commercial diesel (Caltex No.2 diesel), a biodiesel provided by Bioworks Australia Pty Ltd, and a ferrous picrate catalyst manufactured by Fuel Technology Pty Ltd, were used for experimentation. The Fe^{2+} content in the catalyst was within the range of 560 – 600 mgL^{-1} and the catalyst was added into diesel and biodiesel at a dosing ratio of 1:10000 by volume. The specifications of diesel, biodiesel and the catalyst are listed in Table 2. It is seen from Table 2 that the major components of biodiesel is C16 and C18 methyl esters. The C18 components mainly consist of one (C18:1) and two double-bonded (C18:2) methyl ester. Analysis of the catalyst dosed fuels showed that the addition of the catalyst at all dosing ratios had no observable effect on the physical properties, including density, viscosity, flash point, cloud and pour point of both diesel and biodiesel.

2.2 Experimental setup

The experiments were conducted with an air-cooled, single cylinder, four-stroke diesel engine system which was manufactured by Advanced Engine Technology Pty Ltd (AET). Major specifications of the engine are listed in Table 3.

The engine was mounted on an automated bed and coupled with an eddy-current dynamometer which was equipped with a load cell for engine load measurement. Two sensors were placed in the load cell, one for the engine load and the other for the engine speed. These signals were fed into a controller through which the operator can set speed and load of the engine and the dynamometer. Coolant and lube-oil systems were assured by electronically driven pumps to control the operation temperature of the dynamometer and engine. Instantaneous engine oil temperature, engine cylinder head temperature and intake air temperature were recorded and acquired by a computer to monitor the combustion quality within the engine. A schematic diagram of the engine test bench is illustrated in Fig.1.

A one liter container and a digital weighing scale (Acculab LT-3200) on the top deck of the fuel system frame were used to measure the fuel consumed at a fixed time interval 5 minutes in the present experimentation). The fuel container was refilled automatically from a 4 litre fuel reservoir. The digital scale is connected to the data acquisition system so that the brake specific fuel consumption during each test could be calculated and displayed on the computer.

To measure the instantaneous pressure within the cylinder, a high accuracy piezoelectric pressure sensor (Kistler 6052B1) was used, mounted to the cylinder head. The fuel injection pressure was measured using a piezoresistive transducer (Kistler 4067BB2000) connected on the injector side of the pipe linking the injection pump and injector. The needle lift was measured using a Hall-effect proximity sensor which was mounted within the injector nozzle body. In the present experimentation, cylinder pressure, fuel injection pressure and needle lift were measured every five minutes and 20 cycles were acquired in each measurement with a sampling rate corresponding to 0.2 °CA. The cylinder head temperature and dynamometer coolant temperature were measured using thermocouples. All these signals were connected to the input of an A/D board installed on an IBM compatible Pentium PC. This board was capable of acquiring input data at a high rate and recording these high frequency engine signals with acceptable resolutions.

Table 1 A summary of various literature studies on the effects of various metal-based homogeneous combustion catalysts on fuel consumption and exhaust emissions in diesel engines

Catalysts	Fuel Saving	UHC Reduction	CO Reduction	NOx Reduction	Smoke Reduction	Ref.
Platinum	2~9%	27~61%		No Change	N/A	[16]
Ferrocene	N/A	5~35%		-12%	Up to 37%	[18]
Cerium oxide	N/A	25~40%	No Change	Up to 30%	N/A	[12]
Ferrous Picrate	6.6~11.7%	-22 ~ -24%	9~17%	-3~6.6%	N/A	[19]
Ferrous Picrate	2~4.2%	5~40%		-6%	Up to 40%	[13]
Iron Chloride	8.6%	26.6%	52.6%	-4.1%	6.9%	[10]
Barium	1~4%		N/A		35%	[20]

Note: A negative value in the table means that the emission was increased;
UHC denotes unburned hydrocarbons.

Table 2 Main chemical components and physical properties of biodiesel, diesel and catalyst

Species	[a]Component	[a]%	Density (g/ml) (15°C)	Boiling Point(°C)	Viscosity, cSt (40 °C)	Flash Point (°C)	Centane Number
Biodiesel	C16:0 $(C_{15}H_{31})COOCH_3$	18.95%	0.884	205-443	3.40	101	50.1
	C18:0 $(C_{17}H_{35})COOCH_3$	5.96%					
	C18:1 $(C_{17}H_{33})COOCH_3$	41.98%					
	C18:2 $(C_{17}H_{31})COOCH_3$	23.89%					
	C18:3 $(C_{17}H_{29})COOCH3$	2.78%					
Diesel	<C10	8.71%	0.845	200-400	2.02	75	57.1
	C10-C18	75.07%					
	>C18	16.22%					
FTC catalyst			0.876	140-210		43	N/A

[a] GC-MS analys

Table 3 Specifications of SCIEEF Test Engine

Engine Type	Four stoke, direct injection, compression ignition engine
Cylinder Number	Single
Bore (mm)×Stroke (mm)	70×55
Total displacement (L)	0.211
Compression ratio	19.9
Fuel injector body and nozzle	Fuel injection pump: Bosch type, YANMAR PFE-M type Injection timing: 14±1 BTDC Fuel injection pressure: 19.6Mpa Fuel injection nozzle: Hole nozzle YANMAR YDLLA-P type Nozzle: 4 nozzle holes with hole diameter 0.22mm

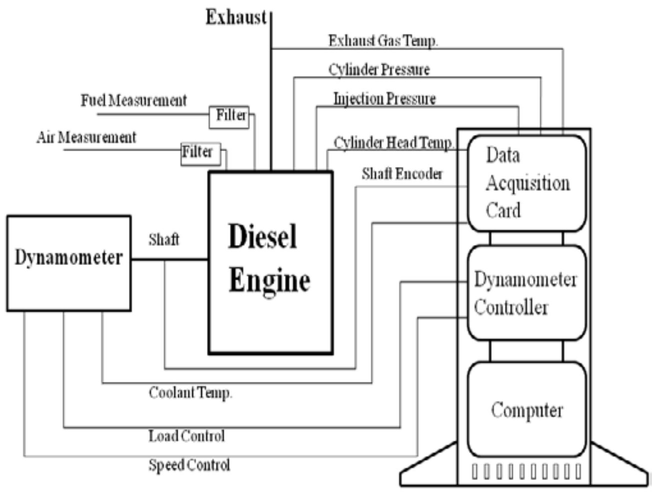

Figure 1 A schematic diagram of the diesel engine test bench

2.3 Parameters Tested

With the measured fuel consumption as described above, the brake specific fuel consumption was calculated, which was defined as the fuel consumption divided by the power. The brake thermal efficiency was also calculated which was defined as the brake work per cycle divided by the amount of fuel chemical energy as indicated by the fuel's lower heating value.

The combustion characteristics and heat release rate based on the data of the measured in-cylinder pressure was calculated.

The heat release rate was calculated based on a single-zone model where the mixture in the cylinder was assumed to be uniform in both composition and temperature and the internal energy of the mixture was calculated using the first law of thermodynamics [1, 21]. The detailed description of the heat release calculation can be found in Ref. [1]. By knowing the cylinder pressure which was experimentally obtained and the instantaneous cylinder volume, the heat release rate was given using the following formula [1]:

$$dQ_n/dt = (1 + c_v/R)\,p(dV/dt) + (c_v/R)\cdot V \cdot (dp/dt) + hA(T - T_w) \quad (5)$$

where *A* is the heat transfer surface area of the combustion chamber walls; Q_n is the gross heat release; C_v is the specific heat capacity of the mixture at constant volume; *p* is the pressure and *V* is the cylinder volume; *h* is the heat transfer coefficient which was calculated based on the Annand equation[21]; and T_w is the wall temperature.

With the measured cylinder pressure and the calculated heat release rate, the typical combustion characteristics can be determined including the cylinder pressure, ignition delay time and combustion duration. These characteristics are shown in Fig. 2. These combustion characteristics reveal some interesting features, which assist in the understanding of the combustion mechanisms associated with the use of the homogeneous combustion catalyst in the diesel engine.

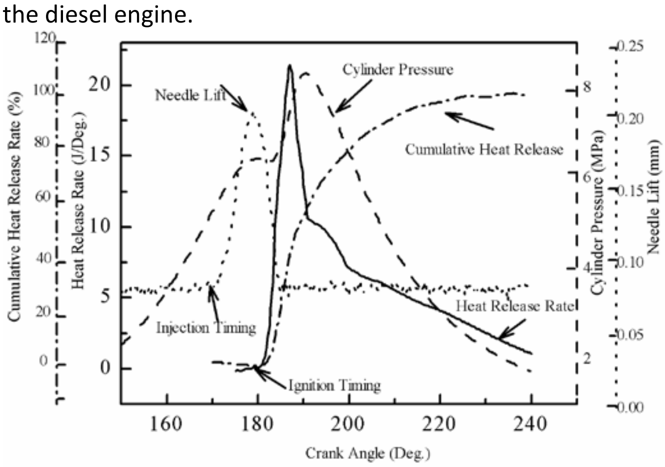

Figure 2 Definitions of combustion characteristics in diesel engines

As shown in Fig.2, the injection timing, which is the start of the fuel injection, was determined at the crank angle where the injector needle lift rises suddenly. The ignition timing, which is the start of the combustion, was determined at the point where the heat release starts. The difference between the ignition timing and the injection timing was defined as the ignition delay time. The end of a combustion process in a cycle was taken as the point where 90% of the cumulative heat release had occurred. The difference between the end of the combustion and the ignition timing was taken as the combustion duration.

2.4 Experimental Procedure

In the present study, a series of tests were conducted at four loads corresponding to about 0.13MPa, 0.21MPa, 0.33MPa and 0.42MPa at the engine speed of 3200rpm.

The experiments were performed by using four fuels, diesel (D), diesel with the catalyst (DC), biodiesel (B), and biodiesel with the catalyst (BC). All experimental runs began with running the engine with the pure diesel fuel in order to determine the baseline of the fuel consumption under each set of the test conditions. The same procedure was repeated for each fuel by keeping operating conditions the same. At each fuel change, the engine was run for at least 30 minutes to purge the remaining previously tested fuel in the engine system. At the end of the test, the fuel was switched back to diesel and the engine was kept running for a while before shutting down in order to flush out the remaining biodiesel in the fuel line and the injection system. Tests on each fuel were repeated five times to ensure the repeatability and statistical validity of the results. All results presented in this study were the average of five measurements under the same conditions, with error bars showing the standard derivations of these measurements.

3. RESULTS AND DISCUSSION

3.1 Fuel efficiency

The dependency of the brake specific fuel consumption on the engine load (BMEP) when the engine was run with the four fuels is presented in Figure 3. It is obvious that the brake specific fuel consumption of tested four fuels decreased with increasing the engine load under the tested conditions. The brake specific fuel consumptions of the biodiesel were greater than that of the diesel. This is probably due to the lower heating value of the biodiesel than that of the diesel. It is also seen that the addition of the catalyst reduced the brake specific fuel consumption of both diesel and biodiesel, which implied that the catalyst promoted the combustion process regardless which fuel was used in the engine. The highest fuel saving was 2.4% for the diesel at the BMEP of 0.21MPa and 2.8% for the biodiesel at the BMEP of 0.42MPa.

Figure 4 shows the variation of the brake thermal efficiency with the engine load (BMEP) for the four fuels. It can be seen that the brake thermal efficiency increased with increasing engine load, reaching the maximum values of 24%-27%. This implies that the energy conversion efficiency was higher at the higher engine load condition due to the higher gas temperature and higher flame temperature [7]. The brake thermal efficiency of the biodiesel was lower than that of the diesel, with the difference increasing with increasing load. However, the brake thermal efficiency of both diesel and biodiesel was improved with the use of the catalyst. For instance, at the engine BMEP of 0.42MPa, the brake thermal efficiency was increased 0.5% for the diesel and 0.8% for the biodiesel.

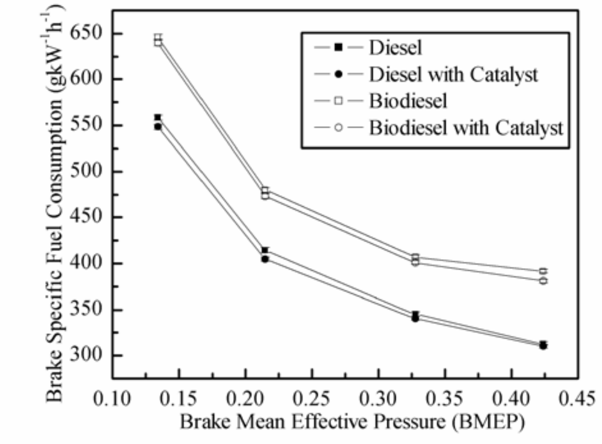

Figure 3 The brake specific fuel consumption as a function of the engine load (BMEP)

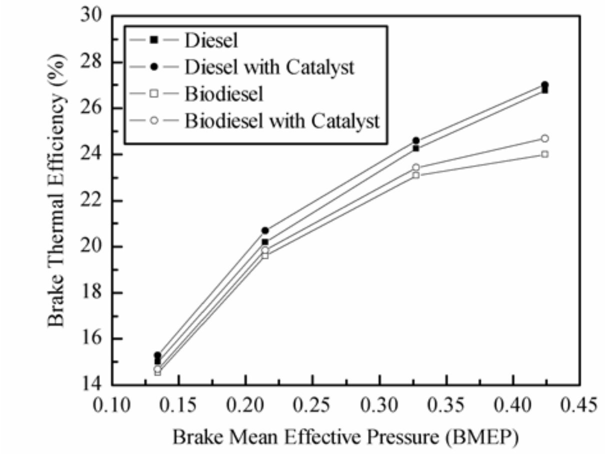

Figure 4 The brake thermal efficiency as a function of the engine load (BMEP)

3.2 Combustion characteristics

In order to understand the observed differences in the fuel efficiency and the brake thermal efficiency, the combustion characteristics of both diesel and biodiesel with and without the catalyst in the engine were analysed.

Figure 5 shows the engine cylinder pressure for the four fuels under the condition of engine speed 3200rpm at the engine BMEP 0.33MPa. In comparison with the pure diesel, the ignition timing was greatly shortened for the biodiesel and the maximum pressure increased slightly. Due to the fact that the ignition timing occurred after the top dead centre (TDC) under the tested conditions, the reduction of the ignition timing implies that the combustion occurred closer to the top dead centre, resulting in a higher maximum pressure. It is also evident that the use of the ferrous-picrate based combustion catalyst slightly reduced the ignition timing and increased the maximum pressure for both diesel and biodiesel. The early peaking pressure characteristic warrants careful attention to ensure that the peak pressure takes place after TDC for safe and efficient operation. Otherwise, a peak pressure occurring close to TDC will cause engine knock and thus affect engine durability. Note that the biodiesel has higher Cetane number than that of the diesel as shown in Table 2. The catalyst advanced the ignition of both diesel and biodiesel slightly as mentioned before and consequently increased the maximum cylinder pressure slightly. However, as seen in Figure 5, the effect of the catalyst on the maximum pressure was not significant. In fact, as discussed below, the effect of the catalyst was more profound in the combustion phase rather than in the ignition phase. Therefore, the engine knock and durability due to the use of the catalyst should not be considered to be an issue.

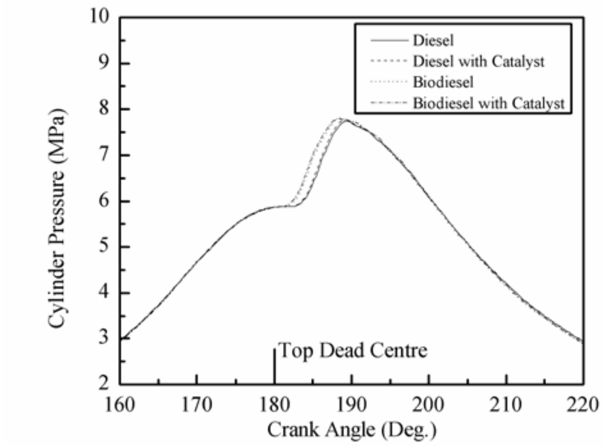

Figure 5 In-cylinder pressure for both diesel and biodiesel dosed with and without the catalyst under engine speed 3200rmp and engine load 0.33MPa

Based on the above measured pressure data, the heat release rates of the four tested fuels were calculated and illustrated in Figure 6. It is very clear that the rate of burning is very high after the ignition, which corresponds to the period of rapid cylinder pressure rise. This was followed by a period of gradually decreasing heat release rate. The commencement of heat release was advanced for the biodiesel compared to that of the diesel, resulting in advanced ignition timing. It can be seen that the maximum heat release rate of biodiesel was lower than that of diesel, specifically, 18.4J/Deg.CA for the diesel and 16.7 J/Deg.CA for the biodiesel. This is because, as a consequence of advanced ignition timing, less fuel was accumulated during the relatively short ignition delay period, which resulted in a lower heat release rate. It is obvious that the heat release started earlier when the catalyst was dosed into both diesel and biodiesel, which implies that the use of the catalyst also advanced the ignition timing.

Figure 7 shows the ignition delay time of the four fuels at the engine speed of 3200 under various engine loads (BMEP). It is seen that the ignition delay time slightly decreased with increasing engine load for both diesel and biodiesel. It is obvious that the ignition delay time of biodiesel was shorter than that of diesel, which is consistent with the literature reports [9]. The difference of the ignition delay time between the diesel and biodiesel was greater under higher engine load. For instance, when the engine fuelled with the biodiesel, the ignition delay was shortened 0.6 °CA (decreasing from 10.6 °CA to 10 °CA) under the BMEP of 0.42MPa while only 0.4 °CA (from 11.2 °CA to 10.8 °CA) under the BMEP of 0.13MPa. Biodiesel usually have constituents having higher boiling point as seen in Table 2. However, the high pressure injection of the biodiesel into a high temperature chamber resulted in a chemical breakdown of the higher weight molecules into products with lower molecular weight on the peripheral region of the spray [22, 23]. Rapid gasification of these lighter compounds on the fringe of the spray leads to an earlier ignition and thus shorter ignition delay time [23].

Adding the catalyst into both diesel and biodiesel resulted in a slightly shorter ignition delay time under all tested engine load conditions. This means that the catalyst participated in the ignition process of fuels and accelerated the chemical reaction rates within the ignition delay period.

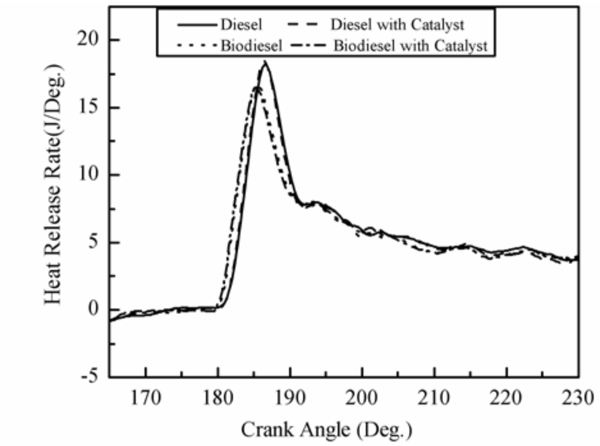

Figure 6 heat release rate and cumulative heat release for both diesel and biodiesel dosed with and without the catalyst under engine speed 3200rpm and engine load 0.33MPa

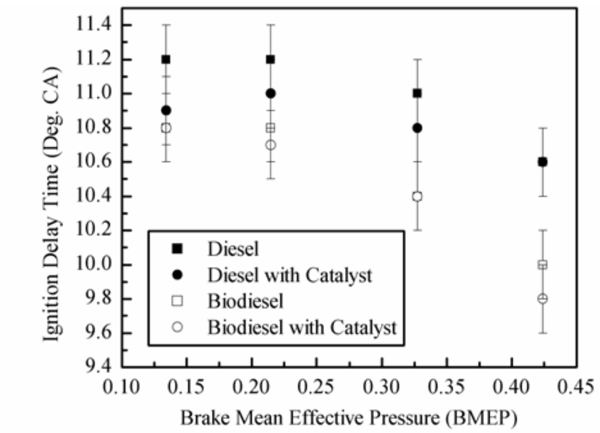

Figure 7 The ignition delay time as a function of the engine load (BMEP) for the tested four fuels

Figure 8 shows the cumulative heat release of the four fuels. Again, it is observed that the ignition timing was advanced for the biodiesel. However, it manifests that the total combustion duration for the biodiesel was longer than that of the diesel. As mentioned earlier, the biodiesel had higher boiling point than the diesel. Those constitutes in the biodiesel with higher boiling may not adequately evaporate during the mixing controlled diffusion combustion phase and continue to burn in the late combustion phase as the piston moved away from the TDC. In addition, biodiesel had a lower heating value than that of diesel so that more fuel was needed to be delivered into the engine to generate the same power when the biodiesel was used. Consequently, more time is required to burn the extra amount of the biodiesel injected into the engine. The longer combustion duration was responsible for the lower thermal efficiency of biodiesel [24] as shown in Figure 4.

It is also seen that the end of the combustion of both diesel and biodiesel was advanced with the addition of the catalyst, shortening the total combustion duration. The reduction of the combustion duration is about two degrees when the catalyst was added into both diesel and biodiesel at the dosing ratio of 1:10000. This observation suggested that the catalyst enhanced the mixing-controlled diffusion combustion in diesel engines, resulting in a faster heat release and shorter combustion duration.

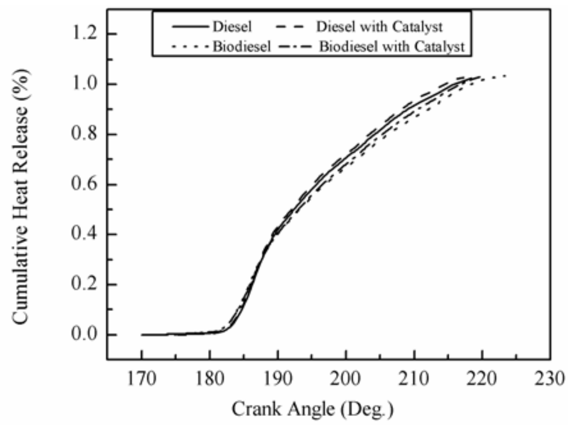

Figure 8 cumulative heat release for both diesel and biodiesel dosed with and without the catalyst under engine speed 3200rpm and engine load 0.33MPa

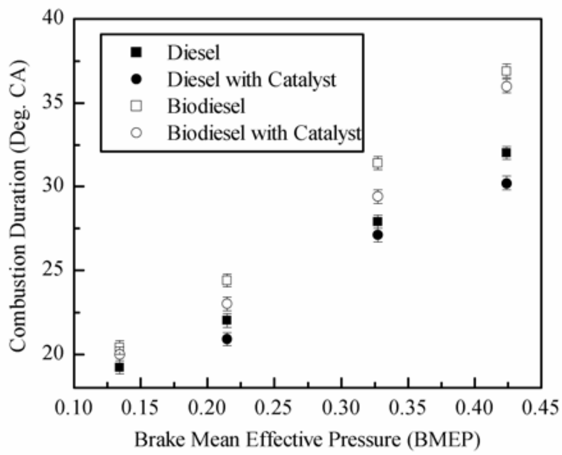

Figure 9 The combustion duration as a function of the engine load (BMEP) for the tested four fuels

The combustion duration of the tested four fuels as a function of the engine loads is shown in Figure 9. It is seen that the combustion duration of all the tested fuels increased with increasing the engine load. With the increase of the engine load, more fuel was injected and consumed, which takes a longer time to complete the combustion. It is obvious that the combustion duration of biodiesel was higher than that of diesel and the difference was greater under higher engine loads. This may help to explain the previous observations as shown in Figure 4 that the thermal efficiency of biodiesel was lower than that of diesel and the difference increased with an increase in the engine load.

A significant reduction in the combustion duration was observed with the catalyst dosed in both diesel and biodiesel. The maximum reduction of 1.7 °CA was observed at the engine BMEP of 0.13 MPa for diesel and 1 °CA for biodiesel at the engine BMEP of 0.33MPa. Under the BMEP of 0.13MPa, the combustion duration was reduced by 3.5 °CA from 23.2 °CA to 19.7 °CA while only 2.2 °CA from 29.3 °CA to 27.1 °CA under the BMEP of 0.42MPa with the use of the catalyst at a dosing ratio of 1:10000.

From Figures 5-9, it is evident that the homogeneous combustion catalyst played a catalytic role during the diesel and biodiesel combustion process in the diesel engine. It promoted the ignition and accelerated the heat release of the fuel combustion in the engine, which allowed time for more complete fuel combustion. Therefore, the brake thermal efficiency was improved and the brake specific fuel consumption was reduced.

4. CONCLUSIONS

The effect of the ferrous picrate based homogeneous combustion catalyst on fuel efficiency and combustion characteristics of biodiesel in a diesel engine has been investigated under various engine loads (BMEP). The main conclusions can be drawn as follows:

The brake specific fuel consumption of biodiesel was ca.15-20% higher than that of diesel. The brake thermal efficiency of biodiesel was lower than that of diesel and the difference was greater under higher engine loads.

The ignition delay time of the biodiesel was shorter than that of diesel with the difference increasing with increasing the load. However, the biodiesel had longer combustion duration than that of diesel with the difference increasing with increasing the engine load.

The use of the catalyst could reduce the brake specific fuel consumption of the biodiesel up to 2.8% and slightly improve the brake thermal efficiency of the biodiesel up to 0.8% under the tested conditions.

The addition of the homogeneous combustion catalyst shortened the ignition delay time of both diesel and biodiesel in the engine, resulting in a slightly higher peak cylinder pressure and a faster heat release rate. In addition, the use of the homogeneous combustion catalyst increased the combustion rate of both diesel and biodiesel, resulting in shorter combustion duration and faster heat release rate.

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