Applied Energy 91 (2012) 166–172

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Effect of a homogeneous combustion catalyst on the combustion characteristics and fuel efficiency in a diesel engine

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ARTICLE INFO

Article history:
Received 8 June 2011
Received in revised form 4 September 2011
Accepted 7 September 2011

Keywords:
Combustion characteristics
Diesel engine
Fuel efficiency
Homogeneous combustion catalyst

ABSTRACT

The influence of a ferrous picrate based homogeneous combustion catalyst on the combustion characteristics and fuel efficiency was studied using a fully instrumented diesel engine. A naturally aspirated four stroke, single cylinder, air cooled, direct injection diesel engine was tested at engine speeds of 2800 rpm, 3200 rpm and 3600 rpm under variable load conditions, with different dosing ratio of the catalyst in a commercial diesel fuel. The results indicated that the brake specific fuel consumption decreased and the brake thermal efficiency increased with the addition of the catalyst. At the catalyst dosing ratio of 1:10,000, the brake specific fuel consumption was reduced by 3.3–4.2% at light engine load of 0.12 MPa and 2.0–2.4% at heavy engine load of 0.4 MPa due to the application of the catalyst. From the in-cylinder pressure and heat release rate analysis, it was found that the catalyst reduced ignition delay and combustion duration of fuel in the engine, resulting in slightly higher peak cylinder pressure and faster heat release rate.

1. Introduction

Diesel engines are widely used in road transportation, remote and small scale diesel-fuelled power generation system, heavy machineries and mining equipments powered by diesel fuel [1–3]. Due to ever increasing fuel costs and the public concerns of the urban air quality due to increased use of petroleum fuels-, many studies have been conducted over the past few decades in an effort to develop cleaner and more efficient diesel engines and their use [4–9]. One possible alternative is homogeneous combustion catalysts added into diesel fuel to improve auto-ignition and combustion quality of diesel within the diesel engines, leading to higher fuel efficiencies. Fuel efficiency is often characterised by the brake specific fuel consumption, which is defined as the rate of the fuel consumption divided by the power produced, allowing the energy conversion efficiency of different engines to be compared directly [2].

Effective homogeneous combustion catalysts should have the following several characteristics: (1) they must be soluble in the diesel fuel homogeneously without settling out or agglomeration during application, storage and on-board consumption; (2) they must have excellent catalytic activity promoting hydrocarbon combustion so that only a very tiny amount of the catalyst is required; and (3) the catalyst would not change the fuel specification significantly and generate the secondary pollutions. Two groups of combustion catalysts are commonly used: metal-containing catalysts and ash-free catalysts [10,11]. Compared to the ash-free catalysts, metal containing compounds are claimed to be more effective [10]. A number of metal ions are found to promote hydrocarbon combustion such as Iron [11–15], Cerium [16–18], Platinum [19,20], Copper [21], Barium [22], Sodium [23] and Manganese [24,25]. These metal-based catalysts are either manufactured in the form of the organometallic compounds or nano-particles using proprietary technologies. With the application of the homogeneous combustion catalysts in diesel engines, up to 12% fuel saving was claimed based on field trial tests and laboratory tests [11].

Manufactured by Fuel Technology Pty Ltd., the homogeneous combustion catalyst used in the present study was a ferrous picrate-water-butanol solution with additives. These additives are mainly short-chain alkyl benzene and its derivatives, which help improve the stability of the ferrous picrate-water-butanol-diesel mixture [11,26]. When applied in proper proportion in diesel engines, this dark green catalyst was claimed to improve fuel efficiency [26]. However, the reported fuel savings due to the use of the catalyst in diesel engines were varied and at times, controversial [11]. In addition, the mechanisms of the working of the homogeneous combustion catalyst in the diesel combustion process in engines remain unclear, which hinders its widespread applications. It is postulated that the catalyst promotes the ignition and heat release rate in diesel engines [12] but some researchers believe that the catalyst only participates in the carbon deposit reaction within engine cylinder [13]. Thus, a science-based, systematic study of the effect of the catalyst on fuel efficiency and combustion characteristics in diesel engines is necessary. Against this backdrop, the

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0306-2619/$ - see front matter
doi:10.1016/j.apenergy.2011.09.007

influence of the combustion catalyst on fuel efficiency and combustion characteristics as a function of catalyst dosing ratio, engine load and speed were investigated on a single cylinder compression ignition engine in the present study.

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 1.

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. There were two sensors 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 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 1 l tank and a digital weighing scale (Acculab LT-3200) on the top deck of the fuel system frame measured the fuel consumed at a fixed time interval (5 min in the present experimentation). The fuel tank was refilled automatically from a 4 l 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.

Fuel injection in the engine was achieved with a YANMAR PFE-M type pump, capable of supplying injection pressures of up to 19.6 MPa. Injection timing was mechanically controlled and was fixed. 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 mounted within the injector nozzle body. In the present experimentation, cylinder pressure, fuel injection pressure and needle lift were measured every 5 min and 10 cycles were acquired in each measurement with a sampling rate corresponding to 0.2° CA. The cylinder head temperature, dynamometer coolant temperature and exhaust gas temperature were measured by thermocouples. All these signals were connected to the input of an A/D board installed on an IBM compatible Pentium PC. This board can acquire input data at a high rate, capable of recording these high frequency engine signals with an acceptable resolution.

Table 1
SCIEEF Test Engine specifications.

Engine type	Four stoke, direct injection, compression ignition (Yanmar L48AE-DG)
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: YANMAR PFE-M type
	Injection timing: 14 ± 1 BTDC (before top dead center)
	Fuel injection pressure: 19.6 Mpa
	Fuel injection nozzle: Hole nozzle YANMAR YDLLA-P type
	Nozzle: 4 nozzle holes with hole diameter 0.22 mm

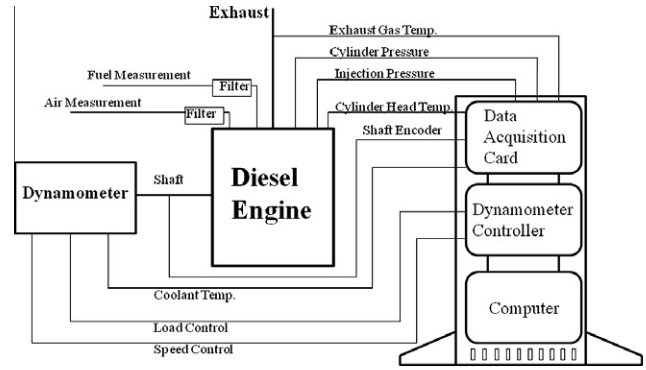

Fig. 1. A schematic diagram of the diesel engine test bench.

3. Parameters tested

The performance of a compression engine is generally characterised by several key parameters including [2,27]:

- The brake specific fuel consumption (bsfc), for measuring the fuel efficiency within a diesel engine. A higher brake specific fuel consumption means a lower fuel efficiency.
- The brake thermal efficiency (bte), for measuring the efficiency and completeness of combustion of the fuel within a diesel engine.
- The heat release rate, for characterising the rate of heat released due to the combustion within a diesel engine.

In each test, by knowing the engine load and speed which were set for a given experiment and kept constant by the engine dynamometer controller, the key engine performance parameters were computed using the following formula:

The brake mean effective pressure, *b.m.e.p.* (in bar).

$$b.m.e.p = (4\pi M/V_c) \times 10^{-5} \quad (1)$$

The brake power, P (in W)

$$P = (M \times 2\pi N)/60 \quad (2)$$

The brake specific fuel consumption, *b.s.f.c.* (in g/kW h).

$$b.s.f.c. = (\dot{m}/P) \times 3.6 \times 10^9 \quad (3)$$

The brake thermal efficiency, *b.t.e.*

$$b.t.e = P/(\dot{m} \times \phi) \quad (4)$$

where M is the engine brake torque, Nm; N is the engine speed, rpm; P is the engine power, W; $\dot{m}$ is the fuel consumption rate, kg/s; Vc is the engine displacement volume, m^3; and ϕ is the lower calorific value of the diesel, MJ/kg.

The heat release rate is calculated based on a single-zone model where the mixture in the cylinder is assumed to be uniform in both composition and temperature and the internal energy of mixture is calculated using the first law of thermodynamics [2]. The detailed description of the heat release calculation can be found in Ref. [2,27]. By knowing the cylinder pressure which was experimentally obtained and the instantaneous cylinder volume, the heat release rate was given using the following formula [2]:

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

where A is the heat transfer surface area of the combustion chamber walls; Qn is the gross heat release; Cv is the specific heat capacity of

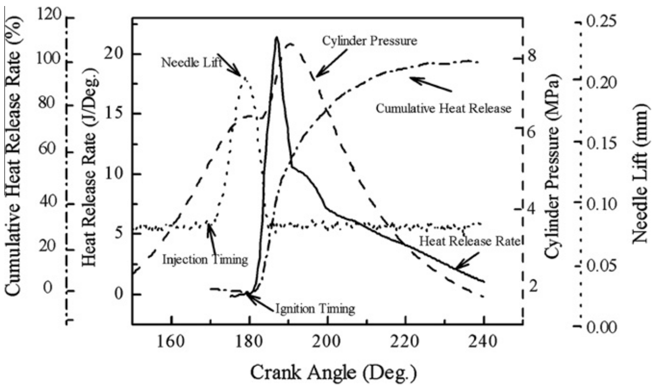

Fig. 2. Definitions of combustion characteristics in diesel engines.

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 [27]; and Tw 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 rise rate, ignition delay and total 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.

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

4. Experimental procedure and statistical analysis

Caltax no. 2 diesel was used as the baseline fuel in the present study and its specifications are listed in Table 2. The homogeneous combustion catalyst was added into the baseline diesel fuel at dosing ratios of 1:20,000, 1:15,000, 1:10,000, 1:5000 (by volume), respectively. It was found that the addition of the catalyst in diesel fuel does not change the fuel specifications.

In the present study, a series of tests were conducted at four loads corresponding to about 100%, 75%, 50% and 25% of the maximum load for three engine speeds at 2800 rpm, 3200 rpm and 3600 rpm.

All experimental runs began with running the engine the pure diesel fuel in order to determine the baseline of the fuel consumption under each of set of the test conditions against which the brake specific fuel consumption data when the homogeneous combustion catalyst was applied to the diesel were compared under the same conditions. The same procedure was repeated for each fuel with a different catalyst dosing ratio by keeping the same operating conditions. At each fuel change, the engine was run for at least 30 min to purge the remaining previously tested fuel in the engine fuel system. Tests on each fuel with a different catalyst dosing ratio 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.

In order to determine the statistical validity of the measured results, a statistical analysis was performed using SPSS software (SPSS Inc, Chicago). The procedure was consisted of an analysis of the variance (ANOVA) and Fisher's least significant difference (LSD) [28]. A statistical level of significance was defined by a (p) value less than or equal to 0.05 which would indicate that the mean value of the brake specific fuel consumption of at least one of the fuels was not equal to the others. Statistical non-significance was defined by (p) value greater than 0.05.

Table 2
Properties of diesel fuel.

Fuel parameters	Caltax no. 2 diesel fuel	Analytical method
Viscosity, cSt (@40 °C)	2.03	ASTM D445
Flash point (°C)	80	ASTM D93
Pour point (°C)	−10	ASTM D97
Distillation range (°C)	180–360	ASTM D86
Density, g/mL (15 °C)	0.8435	ASTM D1298
Sulphur content (ppm)	<10	ASTM D1266

5. Results and discussion

5.1. Effect of the catalyst on fuel efficiency

The effect of the catalyst dosing ratio on the brake specific fuel consumption with the full loaded engine working at speeds of 2800 rpm, 3200 rpm and 3600 rpm, respectively, is shown in Fig. 3. It can be seen that the brake specific fuel consumption decreased with increasing the catalyst dosing ratio under the tested engine conditions. However, the brake specific fuel consumption did not decrease linearly with the catalyst dosing ratio. At the tested engine speeds, the reduction of the brake specific fuel consumption with the catalyst dosing ratio from 0 to 1:15,000 is about three or four times than that with the catalyst dosing ratio from 1:15,000 to 1:5000.

The results of statistical analysis of ANOVA and LSD are presented in Table 3 including the differences in average means of the brake specific fuel consumption for each fuel and the associated p value. The statistical analysis indicates that the brake specific fuel consumption does not change significantly until the catalyst dosing ratio reached 1:15,000 under the three tested speeds. It can also be seen that there is a significant difference in the brake specific fuel consumption between the fuel with catalyst dosing ratio of 1:15,000 and the fuel with the catalyst dosing ratio of 1:10,000, while the brake specific fuel consumption between the fuel with catalyst dosing ratio of 1:10,000 and the fuel with cata-

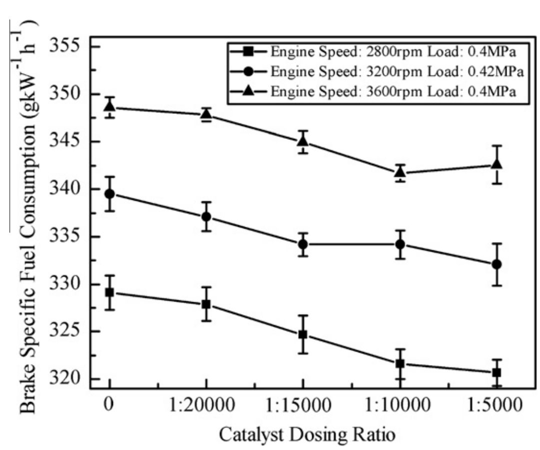

Fig. 3. The brake specific fuel consumption as a function of the catalyst dosing ratio.

Table 3
Results of ANOVA analysis.

		3600 rpm, 0.4 MPa		3200 rpm, 0.42 MPa		2800 rpm, 0.4 MPa	
		Mean difference	*p*-Value	Mean difference	*p*-Value	Mean difference	*p*-Value
Pure diesel	1:20,000	0.78	0.336	2.38	0.037	1.12	0.315
	1:15,000	3.64	<0.0001	5.32	<0.0001	4.42	0.01
	1:10,000	6.92	<0.0001	5.32	<0.0001	7.44	<0.0001
	1:5000	6.02	<0.0001	7.4	<0.0001	8.4	<0.0001
1:20,000	1:15,000	2.86	0.002	2.94	0.012	3.3	0.007
	1:10,000	6.14	<0.0001	2.94	0.012	6.32	<0.0001
	1:5000	5.24	<0.0001	5.02	<0.0001	7.28	<0.0001
1:15,000	1:10,000	3.28	0.001	0	1.0	3.02	0.012
	1:5000	2.38	0.007	2.08	0.065	3.98	0.002
1:10,000	1:5000	−0.9	0.269	2.08	0.065	0.96	0.388

Note: Mean difference in the table refers to the difference between the mean values of BSFC the two fuels compared. *p*-Value indicates the significance of the difference at the 95% confidence level.

lyst dosing ratio of 1:5000 is almost the same. This implies that the optimum catalyst dosing ratio seems to be around 1:10,000.

The dependency of the brake specific fuel consumption on the engine load (BMEP) when the engine was run at engine speeds of 2800 rpm, 3200 rpm and 3600 rpm, respectively, with pure diesel and diesel dosed with different catalyst dosing ratios are is presented in Fig. 4. It is obvious that the application of the homogeneous combustion catalyst reduced the brake specific fuel consumption under all tested load conditions. It is also evident that the homogeneous combustion catalyst has a greater effect when the diesel engine was run under light loads. For example, under the engine speed of 2800 rpm, the use of the homogeneous combustion catalyst reduced the brake specific fuel consumption from 573.1 to 548.9 $gkW^{-1}\,h^{-1}$ (4.2% fuel saving), at the engine load of 0.12 MPa and the catalyst dosing ratio of 1:10,000. As the engine load increased, the influence of the homogeneous combustion catalyst on the brake specific fuel consumption become less significant. Under the tested engine speeds and engine load of 0.4 MPa, the brake specific fuel consumption is reduced by 2–2.4% when the fuel was dosed with the catalyst at a dosing ratio of 1:10,000. The reason may be interpreted as follows. The gas temperature in the cylinder is higher when the engine load is higher, leading to a better burning condition of the fuel mixture, with or without the catalyst. Consequently, the ability of the homogeneous combustion catalyst to promote diesel combustion process at higher engine loads is not as significant as that at light engine loads.

The variation of the brake thermal efficiency on the engine load when the engine was run at engine speeds of 2800 rpm, 3200 rpm and 3600 rpm, respectively, with pure diesel and diesel dosed with catalyst at dosing ratio of 1:10,000 is illustrated in Fig. 5. It can be seen that the brake thermal efficiency increases with increasing engine load, reaching the maximum values of 24–26%. This implies that the energy conversion efficiency is higher at the higher engine load condition due to the higher gas temperature and better burning conditions. It is also evident that the brake thermal efficiency increases due to the use of the homogeneous combustion catalyst under the tested engine conditions. At the engine speeds of 2800 rpm, 3200rom and 3600 rpm and with the catalyst dosing ratio of 1:10,000, the improvement of the brake thermal efficiency reached approximately 0.3–0.8%. It is also seen that the improvement of the brake thermal efficiency is slightly greater in the light load range. For example, under engine speed of 2800 rpm and the catalyst dosing ratio of 1:10,000, the brake thermal efficiency was improved by 0.52% at the engine load of 0.12 MPa but by 0.3% at the engine load of 0.4 MPa.

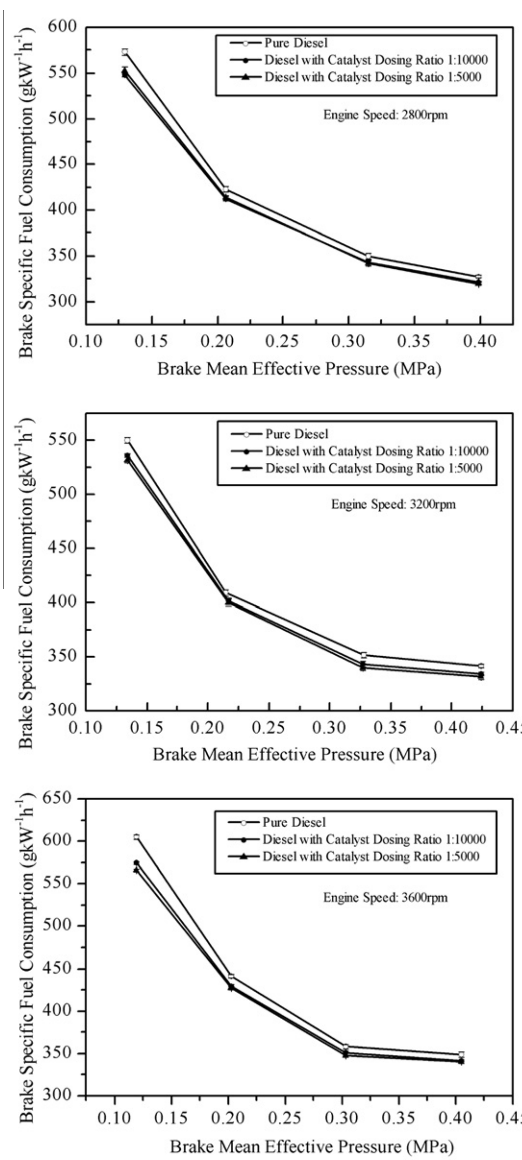

Fig. 4. The brake specific fuel consumption as a function of the engine load (BMEP).

5.2. Effect of the catalyst on combustion characteristics

Fig. 6 illustrates the engine cylinder pressure and pressure rise rate under the conditions of engine speeds 2800 rpm and 3200 rpm at the engine load 0.4 MPa and 0.42 MPa, respectively, when the fuel was dosed with catalyst at different ratios. In comparison with those with the pure diesel, the ignition timing is shortened with the diesel dosed with the homogeneous combustion catalyst and

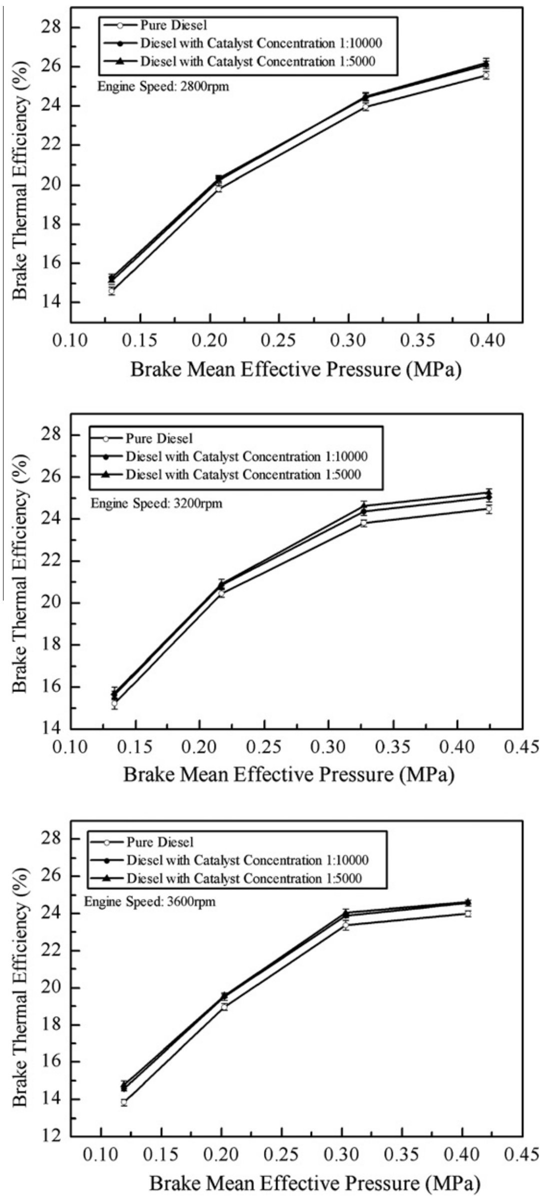

Fig. 5. The brake thermal efficiency as a function of the engine load (BMEP).

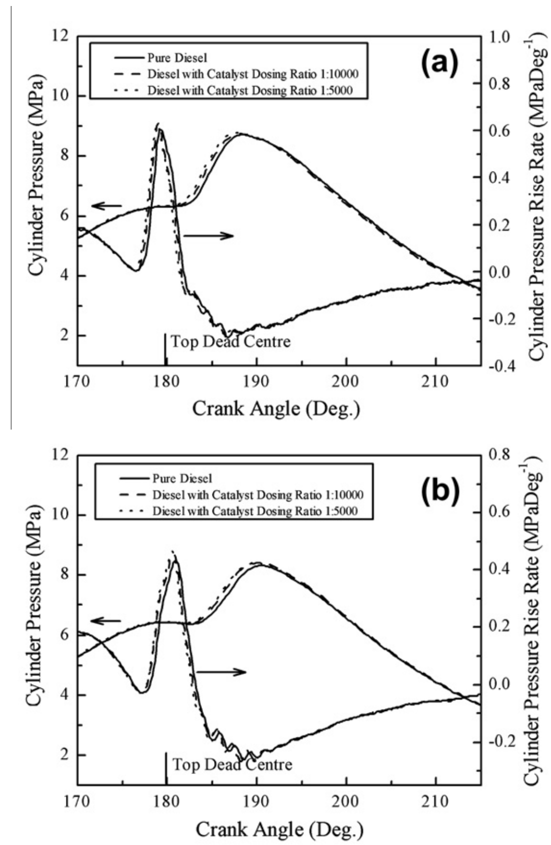

Fig. 6. In-cylinder pressure and pressure rise rate of the engine with the pure diesel and diesel dosed with the catalyst. (a): engine speed: 2800 rpm and engine load: 0.4 MPa; and (b): engine speed: 3200 rpm and engine load: 0.42 MPa.

the maximum pressure increases slightly. Due to the fact that the ignition timing occurred after the top dead center under both conditions seen in Fig. 6, the reduction of ignition timing with the addition of the catalyst implies that the combustion occurred closer to the top dead center, resulting in a higher maximum pressure and a higher rate pressure rise. It is also obvious that the ignition timing and the maximum pressure and pressure rise rate does not change significantly when the catalyst dosing ratio increases from 1:10,000 to 1:5000. This observation is consistent with the finding that the brake specific fuel consumption does not change significantly when the catalyst dosing ratio increased from 1:10,000 to 1:5000 as shown in Fig. 4.

Based on the above measured pressure data, the heat release rates of the pure diesel and the fuel dosed with the catalyst at dosing ratios of 1:10,000 and 1:5000 were calculated and shown in Fig. 7. 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 is followed by a period of gradually decreasing heat release rate. The commencement of heat release is advanced when the catalyst was dosed into the diesel fuel, resulting in a shorter ignition delay. The reduction of the ignition delay is less than 1 degree when the homogeneous combustion catalyst was added into the diesel fuel up to the dosing ratio of 1:5000. The end of the combustion was also advanced with the addition of the catalyst, shortening the total combustion duration. The reduction of the combustion duration is about two degrees when the homogeneous combustion catalyst was added into the diesel fuel up to the dosing ratio of 1:5000.

Fig. 8 shows the effect of the catalyst on the ignition delay and the combustion duration under different engine loads (BMEP) at the engine speed of 3200 rpm. It is seen from Fig. 8a that the ignition delay slightly decreased with increasing engine load for both pure diesel and diesel being dosed with the catalyst. Adding the catalyst into the diesel fuel resulted in a shorter ignition delay under all tested engine load conditions. However, it is evident that the effect of the catalyst on the ignition delay is more significant under lower engine loads. For instance, with the diesel fuel dosed with catalyst at a dosing ratio of 1:10,000, the ignition delay was shortened 0.7 °CA (decreasing from 14.2 °CA to 13.5 °CA) under engine load BMEP of 0.13 MPa while only 0.4 °CA (from 12.7 °CA to 12.3 °CA) under engine load BMEP of 0.42 MPa. It is also manifested that increasing the catalyst dosing ratio from 1:10,000 to 1:5000, the ignition delay did not change significantly. From Fig. 8b, it is seen that the combustion duration for all the tested fuels increased with increasing the engine load. With the increase of the engine load, more fuel is injected and consumed, which takes a longer time to complete the combustion. A significant reduction in the combustion duration was observed with the catalyst dosed in the diesel fuel and this was more remarkable under lower engine load. Under the BMEP of 0.13 MPa, the combustion

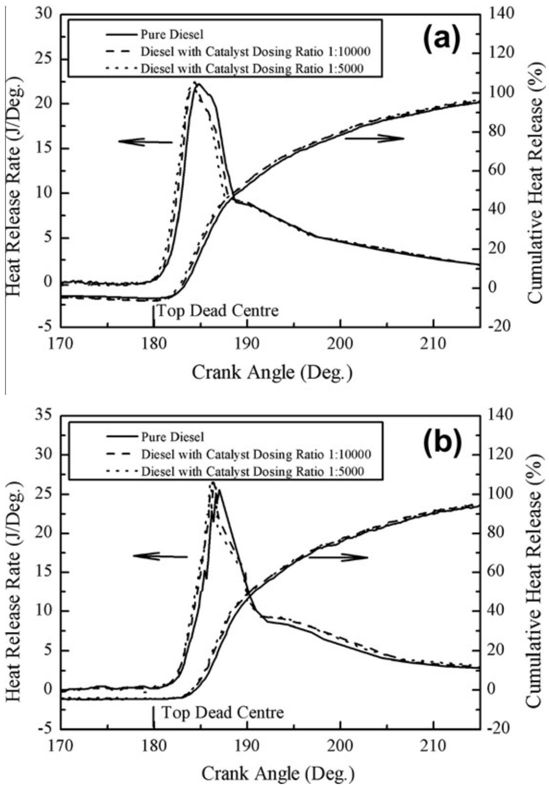

Fig. 7. Heat release rate and cumulative heat release of pure diesel and the diesel dosed with the catalyst. (a): engine speed: 2800 rpm and engine load: 0.4 MPa; and (b): engine speed: 3200 rpm and engine load: 0.42 MPa.

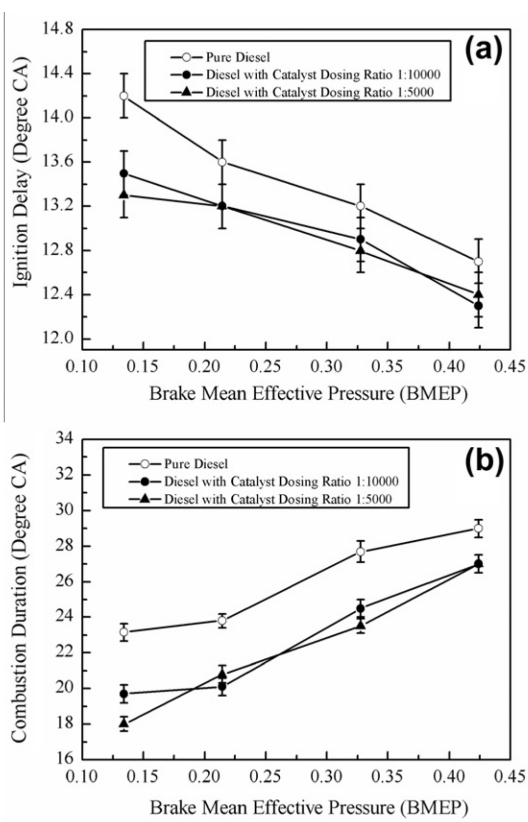

Fig. 8. Effect of the catalyst on the ignition delay and combustion duration under different engine loads (BMEP) at the engine speed of 3200 rpm.

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 0.42 MPa with the use of the catalyst at a dosing ratio of 1:10,000. However, the combustion duration was not further shortened when the catalyst dosing ratio was doubled, especially at higher engine loads.

From Figs. 6–8, it is inferred that the homogeneous combustion catalyst plays a catalytic role during the diesel combustion process in the diesel engine. It promotes the ignition and accelerates the heat release of the diesel combustion in the engine, which allowing time for more complete fuel combustion [29].

6. Conclusions

The effect of the homogeneous combustion catalyst on fuel consumption and combustion characteristics in a diesel engine has been investigated under different engine speeds, loads and catalyst dosing ratios. The main conclusions can be drawn as follows:

1. The brake specific fuel consumption can be reduced up to 4.2% with the addition of the homogeneous combustion catalyst. However, the brake specific fuel consumption reduction does not correlate linearly with the catalyst dosing ratio and, when the catalyst dosing ratio is greater than 10,000, the brake specific fuel consumption becomes less variant.
2. The reduction of the brake specific fuel consumption is greater at light loads. With the catalyst dosing ratio of 1:10,000, the brake specific fuel consumption is reduced by 3.3–4.2% at light engine load of 0.12 MPa and only 2.0–2.4% at higher engine load of 0.4 MPa.
3. The brake thermal efficiency is increased with the addition of the catalyst. The brake thermal efficiency is increased by 0.3–0.8% at engine speeds of 2800 rpm, 320 rpm and 3600 rpm with the catalyst dosing ratio of 1:10,000.
4. The addition of the homogeneous combustion catalyst shortens the ignition delay and combustion duration of diesel in the engine, resulting in slightly higher peak cylinder pressure and faster heat release rate.

Acknowledgments

This project is supported by the Australia Research Council under the ARC Linkage Projects Scheme (Project Number: LP0989368) in partnership with Fuel Technology Pty Ltd. and BHPBilliton Iron Ore Pty Ltd.

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