Evaluation of an iron-based organometallic combustion catalyst for reduction of exhaust emissions from diesel engines

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Abstract

A series of experimental investigations were carried out to examine the effect of a iron-based organometallic combustion catalyst on the emission characteristics from a four-stroke, direct-injection, single cylinder diesel engine. Engine tests, with and without the catalyst in the diesel fuel, were conducted. Results showed a maximum of 2.7% reduction on brake specific fuel consumption with the catalyst treated fuel, due to the catalytic improved fuel efficiency. The exhaust emissions evaluated in this study included smoke, CO, total unburnt hydrocarbons (UHC), CO_2 and NOx. Significant improvements were achieved in terms of the smoke, CO, UHC and CO_2, reductions due to the application of the combustion catalyst, by the maximum ratio of 33.4%, 20.5%, 16.2% and 6.1%, respectively. A slight increase up to 5.7% in the NOx emissions was also observed as a penalty. The results demonstrated that the Fe-based combustion catalyst provides an alternative approach to controlling the severe diesel engine emissions.

Keywords: combustion catalyst, diesel engine, exhaust emission, iron, organometallic

1. Introduction

Recently, under the enforcement of increasingly stringent emission regulations, advanced technologies to control diesel exhaust emissions are becoming essential and receiving more and more interests [1, 2]. One of the effective approaches is to add metal-based combustion catalysts into diesel fuel for promoting diesel combustion, reducing fuel consumption and lowering diesel engine emissions[3, 4]. In terms of molecular composition, such additives normally contain a metallic part as the active material and an organic part which makes the molecules oil-dissolvable, thus also named as homogeneous combustion catalysts (HCCs). These metal catalysts include platinum (Pt), cerium (Ce), manganese (Mn), magnesium (Mg), iron (Fe), nickel (Ni), calcium (Ca) and copper (Cu)[5-8]. Based on previous published works, it has been shown that tiny amount of metal-based HCCs (ppm, by weight or volume) is able to highly improve the diesel engine performances and effectively reduce diesel exhaust emissions.

The current study is particularly interested in iron, which has proved to play an important role in emission control by numerous studies in premixed or diffusion flames, drop-tube furnaces, boilers and diesel engines [9-11]. A novel iron-based combustion catalyst has been employed in this paper, which consists of an organometallic compound -ferrous picrate as the active agent dissolved in a solvent naphtha base. It has been shown from our previous laboratory work [12-14] that the catalyst is able to improve fuel efficiency and reduce the brake specific fuel consumption up to 4.2% under tested engine operational conditions. However, the ability of the aforementioned catalyst for eliminating exhaust emissions has never been systematically evaluated and quantified.

The objective of this work is to examine the effectiveness of the novel combustion catalyst for emission reduction from a single cylinder diesel engine. The diesel fuel with or without catalyst was tested under steady state engine conditions to avoid uncertainties associated with the complex engine operations. Although this study was focused on the effect of the catalyst on emission characteristics, the fuel consumption measurement was also included which was useful for the interpretation of the emission results.

2. Equipments and Experimental Methods

2.1 Fuels

A standard No.2D diesel fuel purchased from a local Caltex service station (Caltex Australia Ltd.) was used as the baseline neat diesel. The Fe-based combustion catalyst was provided by Fuel Technology Pty. Ltd. The manufacturer recommended dosage ratio was 1:3200 (catalyst to diesel) by volume. We also used a higher dosing ratio of 1:1600 to fully assess the effect of the catalyst on the engine emission characteristics.

Key physical properties for each fuel used were determined prior to the engine tests in order to ascertain the difference in the diesel after being treated by the catalyst, if any. The specifications were shown in Table 1. The neat diesel fuel was denoted as “ND”. The catalyst treated diesel fuel was abbreviated as the catalyst name and dosage ratio, i.e. “FTC-D (1:3200)”, “FTC-D (1:1600)”.

Table 1 Fuel specifications of tested diesel fuels

Fuel Properties	**ND**	**FTC-D (1:3200)**	**FTC-D (1:1600)**	**Method**
Density (kg/m^3@ 15°C)	847.5	847	847.2	ASTM D1298
Viscosity (cSt @ 40°C)	2.03	2.03	2.01	ASTM D445
Flash point (°C)	74	75	74	ASTM D93
Pour point (°C)	-15	-15	-15	ASTM D97
Distillation range (°C)	171-360	173-361	174-360	ASTM D86
Calculated cetane index (CCI)	48.2	48.4	48.6	ASTM D4737

2.2 Experimental setup and procedure

The experiments were conducted on a 211cm^3, air-cooled, four-stroke and direct-injection single cylinder diesel engine (YANMAR L48AE-D, AET Ltd.). The main engine specifications are: bore 70mm, stroke 55mm, compression ratio 19.9:1, maximum output 3.5kW at 3600rpm. The engine was coupled to a water-cooled Zöllner TypeA-100 electric dynamometer with the maximum power of 20HP for load control. An automatic control system was used to alter the engine speed and output torque.

A 1L fuel tank sat on top of a digital weighing scale (Acculab LT-3200) was connected to the fuel delivery line for measuring the fuel consumed at a fixed time interval. The digital scale was linked to a computer with data acquisition systems to record and calculate the fuel consumption at each engine test run. AVL Digas 4000 emission analyser was employed to measure the concentrations of CO, HC, CO_2 by infrared analysis and NOx, O_2 in the exhaust by electrochemical measurement. The particulate matter (PM) emission was tested by monitoring the smoke opacity with Bosch RTM 430 infrared opacimeter. The two instruments were calibrated prior to engine tests.

The experiments were conducted with three tested fuels with engine operated at three speeds 2800rpm, 3200rpm, 3600rpm under 75% load (5.5Nm) condition. In each test involving a new fuel, the engine system was purged with the new fuel mixture for a period of time to prevent the fuel in the prior test from affecting the subsequent engine performance tests.

3. Results and Discussion

3.1 Effects on fuel properties

From Table 1, it was observed that the main physical properties of diesel fuel, including flash point, pour point, density, viscosity, distillation range and cetane index were not significantly influenced by the addition of the Fe-based combustion catalyst, due to its extremely low dosage ratio in the diesel fuel. Similar findings were also reported by Yang et al. [7] when using 400ppm Mn-based catalyst in diesel fuel. The study on fuel physical properties ensured that the Fe-based combustion catalyst used in this study was ready to use with no requirements on engine retrofits and have no adverse effects on the single engine parts of the whole system.

3.2 Effects on fuel consumptions

The brake specific fuel consumption (BSFC) value measures how efficiently the engine is producing work by using the fuel supplied [15]. As shown in Fig.1, the BSFC of the FTC catalyst treated fuel was found to be lower than that of neat diesel for all engine tests. The maximum fuel saving for FTC-D (1:3200) was achieved by 2.1% and that for FTC-D (1:1600) was by 2.7%, at the test condition of 2800rpm and 75% load respectively. The reduced fuel consumption was a result of the improved fuel combustion by the catalytic effect. This finding was followed with the observations of shortened ignition delay, increased cylinder pressure and faster heat release rate in our previous work [14].

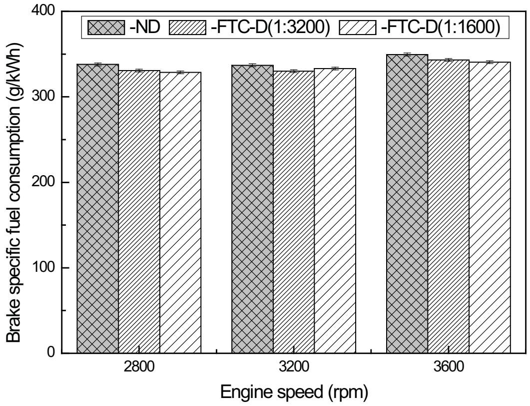

Fig. 1 BSFC of tested fuels at various speeds

3.3 Effects on engine emissions

All the smoke and gaseous emission data acquired were averaged within 10 measurements under each tested engine condition and normalised on the basis of per unit power output to eliminate the uncertainties associated with the power output at each speed. The average values were plotted in the following figures with error bars showing the standard deviations.

The smoke emissions of the tested three fuels are illustrated in Fig.2. It is obvious that the smoke emission was significantly suppressed by the addition of the catalyst at all tested speeds. The maximum reductions of smoke level for FTC-D (1:3200) and FTC-D (1:1600) were 30.4% and 33.4% at 2800rpm, respectively. Generally, for a direct-injection (DI) diesel engine, the highest soot formation was found in the core region of each fuel spray, specifically in fuel-rich zone with high temperature and pressure [15]. The significant smoke reduction due to the addition of Fe-based catalyst may indicate that the carbon oxidation in fuel-rich area is promoted by the catalyst and therefore fewer particles emitted. Similar explanation was found in the work of R. Anand et al. [16]by applying ferric chloride ($FeCl_3$) in a diesel engine fuelled with biodiesel.

The comparison between carbon monoxide (CO) emissions for the neat diesel and the catalyst treated fuels is shown in Fig.3. CO emissions from internal combustion engines are mainly controlled by the fuel-air equivalence ratio, since diesel engines normally operate on the lean side of fuel combustion [15], the CO emissions are not as severe as spark-ignition engines. From Fig.3, it is clearly seen that CO emitted by the catalyst treated fuel was much lower than that for the corresponding neat diesel, with the maximum reduction of 18.8% and 20.5% for FTC-D (1:3200) and FTC-D (1:1600) fuels at 2800rpm, respectively. The decrease in the CO emissions showed that the diesel fuels treated with Fe-based catalyst were burned better inside the engine than that without adding the catalyst.

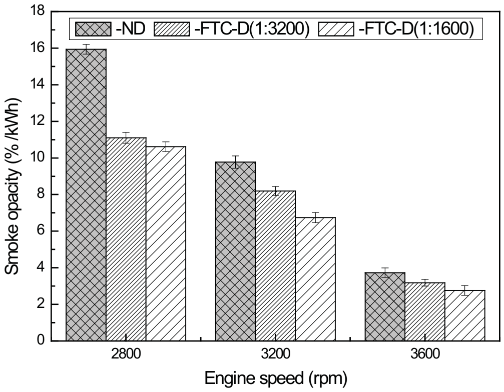

Fig. 2 Smoke emissions of tested fuels at various speeds

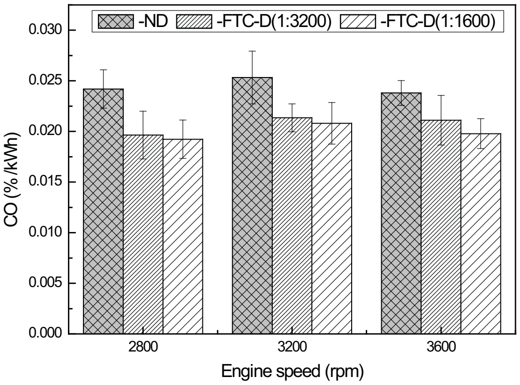

Fig. 3 CO emissions of tested fuels at various speeds

The total unburned hydrocarbon (UHC) emission characteristics of the three tested fuels under controlled engine conditions are plotted in Fig.4. The formation of unburnt hydrocarbons is a consequence of incomplete combustion. As shown in Fig. 4, the UHC emissions from the catalyst treated fuels were lower than that from the baseline diesel in all cases, a fact collectively attributed to the catalytic combustion effect induced by the Fe-based combustion catalyst. The highest UHC reductions were achieved with the ratio of 12.7% for FTC-D (1:3200) and 16.2% for FTC-D (1:1600) at 3600rpm, respectively.

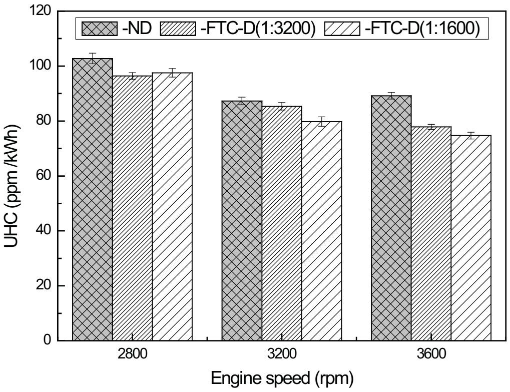

Fig. 4 UHC emissions of tested fuels at various speeds

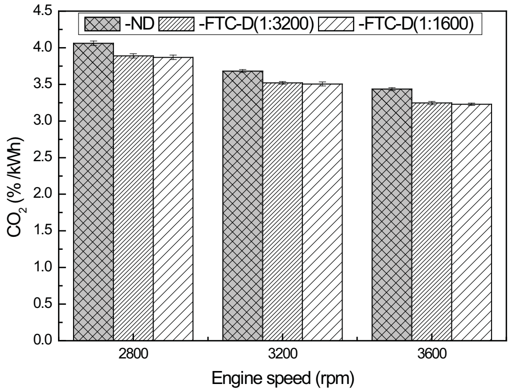

Fig. 5 CO_2 emissions of tested fuels at various speeds

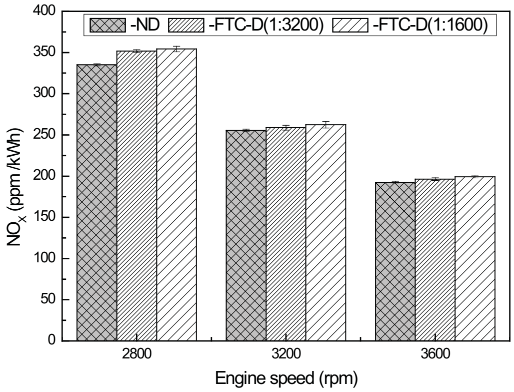

Fig. 6 NOx emissions of tested fuels at various speeds

The effectiveness of the catalyst on carbon dioxide (CO_2) emissions per unit of power output at various operational conditions is depicted in Fig. 5. Lowered CO_2 emissions were observed from the catalyst treated fuels, due primarily to the reduced fuel consumption in each engine cycle run. The maximum reductions of CO_2 were observed at 3600rpm at the ratio of 5.5% for FTC-D (1:3200) and 6.1% for FTC-D (1:1600), respectively.

The influence of the catalyst on oxides of nitrogen (NOx) emissions at three tested speeds is shown in Fig.6. NOx produced inside diesel engines generally consists of nitric oxide (NO) as the predominant product and small amounts of nitric dioxide (NO_2).

NOx formations are primarily promoted by high adiabatic flame temperature and oxygen contents in local combustion region [15]. From Fig. 6, it is noticed that the NOx emissions were relatively higher from the catalyst treated fuels, with the highest ratios of 5.0% for FTC-D (1:3200) fuel and 5.7% for FTC-D (1:1600) fuel at 2800rpm. The increased NOx emission was also found by other researchers [16] using Fe-based metallic catalyst in the form of $FeCl_3$ in biodiesel, 4.1% of extra NO emission was reported in this study. It was believed in the above mentioned paper that due to the presence of the catalyst, more nitrogen is oxidised into nitric oxide during combustion process. Similarly, in our engine tests, higher peak cylinder pressure and heat release rate were observed when fuelled with catalyst treated fuel, which is probably the reason for the slightly increased NOx emissions. Efforts are currently being made to further study the engine combustion characteristics in order to reveal much confident explanations for the rich-NOx emissions.

4. Conclusions

The application of a novel Fe-based organometallic combustion catalyst in the form of ferrous picrate in diesel engines has been experimentally evaluated in terms of emission characteristics under various engine operational conditions. Based on the experimental results, the following conclusions may be drawn:

1. The key fuel properties such as density, viscosity, flash point, pour point, distillation range and cetane index were not influenced by the addition of the Fe-based metallic catalyst, due to its ultra low dosage ratio in diesel fuel.
2. The FTC catalyst is able to decrease specific fuel consumptions by the catalytic effect to the combustion process. A maximum of 2.1% and 2.7% fuel saving was observed for FTC-D (1:3200) and FTC-D (1:1600) respectively, under optimised engine condition.
3. Significant reductions in the smoke, CO and UHC emissions were observed when the engine was fueled with the catalyst treated fuels. For FTC-D (1:3200) fuel, the maximum reductions of smoke, CO and UHC were by the ratio of 30.4%, 18.8% and 12.7%, while for FTC-D (1:1600) fuel were by the ratio of 33.4%, 20.5% and 16.2%, respectively.
4. Slight decrease in the CO_2 emission per unit of power output was also obtained with the highest reduction ratio of 5.5% for FTC-D (1:3200) fuel and 6.1% for FTC-D (1:1600) fuel. NOx emissions were found to be increased by 5.0% and 5.7% from the two catalyst-treated fuels, which was a result of the improved combustion efficiency caused by the catalyst.

It is concluded that the addition of the ferrous picrate as a combustion catalyst in diesel fuel is able to effectively improve fuel consumption and smoke, CO, UHC, CO_2 emissions. The Fe-based combustion catalyst can be widely used as a suitable alternative tool to control the severe diesel engine exhausts.

5. Acknowledgments

This research was supported under the Australian Research Council's Linkage Projects funding scheme (project number: LP0989368) and financially supported by Fuel Technology Pty. Ltd. and BHPBilliton Iron Ore Pty. Ltd.

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