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The effect of a homogeneous combustion catalyst on exhaust emissions from a single cylinder diesel engine

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HIGHLIGHTS

- ▶ Effect of a Fe-based homogeneous catalyst on diesel engine emissions was studied.
- ▶ The fuel properties were not altered by the addition of the catalyst.
- ▶ The catalyst led to 4% fuel saving under the tested conditions.
- ▶ The catalyst reduced engine emissions by up to 39% smoke, 21% CO and 13% UHC.

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ABSTRACT

This paper reports a series of experimental investigations into the effect of an Fe-based homogeneous combustion catalyst on the emission characteristics from a four-stroke single cylinder diesel engine. The catalyst contained ferrous picrate as the active ingredient in a composite organic solvent mixture which could be homogeneously dissolved into a commercial diesel fuel at ultra low dosage ratios. The engine tests were conducted at four different engine loads and at two steady speeds of 2800 rpm and 3200 rpm, respectively. Engine exhaust emissions of CO, unburnt hydrocarbons (UHCs) and NOx were measured using an AVL gas analyser and the particulate emissions were evaluated in terms of smoke opacity using a Bosch smoke meter. The results showed that, in addition to the benefit of improved fuel efficiency, the homogeneous combustion catalyst significantly reduced the emissions of particulate matter, CO and UHC from diesel engines. Compared with the reference diesel, up to 3.7% reduction in the brake specific fuel consumption was achieved when the diesel fuel was treated with the catalyst. The use of the catalyst also led to significant reductions in the particulate matter, CO and UHC emissions, with the maximum reductions being 39.5%, 21.1% and 13.1%, respectively. The NOx emissions, however, increased slightly, by ca. 6%, which was consistent with the improved combustion performance as reasonably expected.

1. Introduction

Compression ignition (CI) engines, also known as diesel engines, are widely used in transportation, heavy machinery and power generation due to their higher efficiencies, power outputs and durability compared with spark ignition petrol engines. However, the ever-increasing demand for diesel engines has also led to increased emissions of a range of pollutants with adverse effects on the environment and human health [1,2]. Diesel engine exhausts are typically severe, which contain, depending on the engine design and operational parameters, large amounts of particulate matter (PM) or smoke emissions and varying amounts of carbon monoxide (CO), unburned hydrocarbons (UHCs), nitrogen oxides (NOx), sulphur oxides (SOx) and carbon dioxide (CO_2) [3,4]. Recently, under the enforcement of increasingly stringent emission regulations, advanced technologies to control diesel engine exhaust emissions have become essential and received more and more research and development interests [5–9].

Based on previous work, the addition of metal-based combustion catalysts to diesel fuel has shown to be an effective approach to improving diesel combustion, reducing fuel consumption and more importantly, lowering engine emissions [10–12]. At the molecular level, these catalysts consist of a metallic component as the active ingredient and a composite organic solvent which dissolve in liquid hydrocarbon fuels such as diesel, thus also named as homogeneous combustion catalysts (HCCs). These metal-based HCCs include platinum (Pt), cerium (Ce), manganese (Mn), magnesium (Mg), iron (Fe), nickel (Ni), calcium (Ca) and copper (Cu) [13–18]. Valentine et al. [13] studied the effect of a bimetallic Pt/Ce

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catalyst on the engine performance when fuelled with diesel dosed with 4–8 ppm of the active metals and achieved 10–25% reduction in PM and 10–30% reductions in UHC and CO emissions, together with 5–7% improvement in fuel economy. Guru et al. [18] reported the influence of Mn and Mg based catalysts on the performance of diesel engines at the metal to fuel dosage ratio of 8 μmol/L and 16 μmol/L and found that the two catalysts were able to achieve the maximum reduction ratios of 3.1% and 2.0% for fuel consumption, 16.4% and 13.4% for CO emission, 29.8% and 17.9% for PM emission, respectively. May and Hirs [19] conducted a series of engine tests by using an Fe/Mg bimetallic-organo combustion catalyst containing 50 ppm Fe and 10 ppm Mg, respectively, and observed significant reductions in fuel consumption due to more efficient combustion with the catalyst treated fuel.

Among these aforementioned metals, iron has also been shown to play an important role in emission reductions. Since Shayeson [20] in 1967 for the first time detected the smoke reduction in a jet engine by applying iron compounds, various laboratory studies have been carried out to explore the effects of iron in premixed [21] or diffusion flames [22], drop tube furnace [23], boilers [19] and diesel engines [24,25], in the forms of iron pentacarbonyl ($Fe(CO)_5$), ferrocene ($Fe(C_5H_5)_2$), iron naphthenate, and iron chloride ($FeCl_3$). The present contribution details a laboratory study of the diesel engine emission characteristics involving an Fe-based HCC, which consists of an organometallic compound, ferrous picrate, as the active ingredient. The catalyst can be directly mixed with commercial diesel fuel at an ultra low dosage ratio. Field trials and our previous laboratory studies [26–28] have shown significant benefits in improved fuel economy and engine performance. It was found [27,28] that the catalyst can reduce the combustion duration of the fuel in the engine and result in a faster rate of heat release and higher peak cylinder pressure, thus enhancing the fuel combustion efficiency and saving the fuel consumption rates. However, there is a lack of systematic evaluations of the efficacy of the catalyst in controlling the engine emissions.

In the current study, diesel fuels, with or without the catalyst, were tested in a single cylinder diesel engine. Exhaust emissions including CO, UHC, NOx and PM were measured under various engine operating conditions.

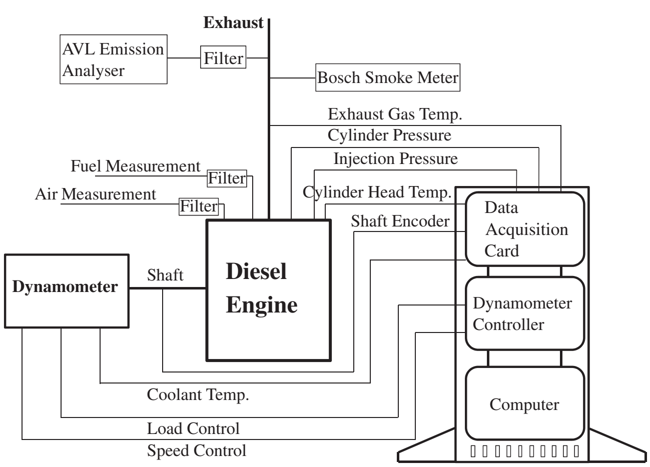

Fig. 1. Schematic diagram of the diesel engine system.

2. Experimental

2.1. Test engine and instrumentation

The experiments were conducted on a single cylinder, naturally-aspirated, four-stroke, air-cooled, direct-injection YANMAR L48AE diesel engine (AET Ltd.). The engine had 70 mm bore, 55 mm stroke, 211 cm^3 displacement, compression ratio of 19.9:1 and was capable of delivering 3.5 kW rated brake power at the speed of 3600 rpm. A water-cooled, Zöllner A-100 electric dynamometer was directly coupled to the engine output shaft for providing various load conditions. Calibrated sensors/probes were installed to monitor the ambient and intake air temperatures, oil temperature, dynamometer coolant temperature and the exhaust temperature. A schematic layout of the diesel engine test system is shown in Fig. 1.

A 1L fuel tank sitting on a digital weighing scale (Acculab LT-3200) was connected to the fuel delivery line for measuring the instantaneous fuel consumption at a fixed time interval. For exhaust measurements, an AVL Digas 4000 emission analyser was used to analyse the concentrations of CO, UHC, and CO_2 by an infrared method and NOx and O_2 by an electrochemical method. PM emission measurement was achieved by monitoring the smoke opacity of the exhaust with a Bosch RTM 430 infrared opacimeter. SOx emission was not concerned in the present study since the compositions of the catalyst were not expected to introduce extra sulphur into diesel fuel. To ensure the high accuracy of each measurement, the instruments were carefully calibrated before each test. Table 1 shows the accuracies and ranges of the employed instruments for the emission measurements.

2.2. Fuels

A commercial diesel fuel was obtained from a local Caltex service station (Caltex Australia Ltd.) and used as the reference diesel in this study. Two homogeneous combustion catalysts, FTC and FPC, were provided by Fuel Technology Pty., Ltd. Both catalysts had similar compositions with different amounts of ferrous picrate as the active ingredient dissolved in a composite organic solvent made of short-chain alkyl benzene and its derivatives, which help improve the stability of the ferrous picrate–water–butanol–diesel mixture [22]. The Fe^{2+} contents in FTC and FPC were 180 mg/L and 560 mg/L, respectively. In the experimentation, the catalysts were respectively added into the reference diesel at two dosing ratios, namely, 1:3200 for FTC and 1:10 000 for FPC (by volume) due to the different concentrations of ferrous picrate in the FTC and FPC catalysts. For convenience, the reference diesel fuel was denoted as

Table 1
Specifications of the instruments used for the emission tests.

Instrumentation	Measurement	Measuring range	Accuracy	Measurement principle
AVL digas 4000	CO	0–10% by vol.	0.01%	Infrared measurement
	CO_2	0–20% by vol.	0.1%	
	UHC	0–20 000 ppm vol.	1 ppm	
	NOx	0–4000 ppm vol.	1 ppm	Electrochemical measurement
	O_2	0–4% by vol.	0.01%	
		4–22%	0.1%	
Bosch RTM 430 infrared opacimeter	Opacity	0–100%	0.1%	Optical LED measurement