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Regulated and unregulated emissions from a diesel engine fueled with diesel fuel blended with diethyl adipate

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ABSTRACT

Experiments were carried out on a four-cylinder direct-injection diesel engine operating on Euro V diesel fuel blended with diethyl adipate (DEA). The blended fuels contain 8.1%, 16.4%, 25% and 33.8% by volume fraction of DEA, corresponding to 3%, 6%, 9% and 12% by mass of oxygen in the blends. The engine performance and exhaust gas emissions of the different fuels were investigated at five engine loads at a steady speed of 1800 rev/min. The results indicated an increase of brake specific fuel consumption and brake thermal efficiency when the engine was fueled with the blended fuels. In comparison with diesel fuel, the blended fuels resulted in an increase in hydrocarbon (HC) and carbon monoxide (CO), but a decrease in particulate mass concentrations. The nitrogen oxides (NO_x) emission experienced a slight variation among the test fuels. In regard to the unregulated gaseous emissions, formaldehyde and acetaldehyde increased, while 1,3-butadiene, ethene, ethyne, propylene and BTX (benzene, toluene and xylene) in general decreased. A diesel oxidation catalyst (DOC) was found to reduce significantly most of the investigated unregulated pollutants when the exhaust gas temperature was sufficiently high.

1. Introduction

The use of oxygenated fuels as alternative fuels or as additive in diesel fuel for diesel engine is beneficial to reducing both diesel fuel consumption and pollutant emission. It is commonly accepted that cleaner combustion can be achieved when a diesel engine is fueled with oxygenated fuels, especially in the reduction of particulate emissions (Miyamoto et al., 1998; Akasaka and Sakurai, 1997). However, various oxygenated fuels have different physical and chemical properties which might lead to different effects on engine performance and exhaust gas emissions.

Among the many oxygenated fuels, diethyl adipate (DEA; $C_{10}H_{18}O_4$) has rarely been investigated. DEA was screened and selected as one of eight oxygenates, out of a total of 71 oxygenates, for testing on advanced diesel engines (Natarajan et al., 2001). Actually, DEA can be mixed with diesel fuel at normal temperature and pressure. It has high oxygen content, low sooting tendency and suitable physico-chemical properties for application to diesel engine. Moreover, DEA is a colorless liquid which has relatively low toxicity, corrosivity and reactivity. It can be derived from the esterification of adipic acid and ethanol in the presence of concentrated sulfuric acid, and is readily available in Chinese mainland. The cost of DEA is higher than that of diesel fuel at present. DEA has been screened and selected for investigation by Natarajan et al. (2001) based on several criteria, one of which is that the cost of DEA could be competitive when it is used in large quantity. Manuel et al. (2001) tested the eight oxygenates screened by Natarajan et al. (2001) and found that reduction of particulate emissions could be achieved by adding DEA to diesel fuel, however there could be an increase in NO_x and CO emissions. Their test on DEA was carried at a single mode of 0.42 MPa at 2300 rev/min. Ren et al. (2007) studied the combustion and emission characteristics of diesel-DEA blends. On the emission side, they only measured smoke opacity and NO_x.

The literature shows that there is lack of comprehensive investigation on the emissions of a diesel engine fueled with diesel-DEA blends, in particular the unregulated emissions from the diesel-DEA blends have not been investigated before. The present study is aimed to study the regulated and unregulated emissions of a diesel engine fueled with Euro V diesel fuel blended with different proportions of DEA under five engine loads at a steady speed of 1800 rev/min. The regulated emissions including HC, CO, NO_x and particulate mass concentrations, while the unregulated emissions include formaldehyde, acetaldehyde, 1,3-butadiene, ethene, ethyne, propylene and BTX (benzene, toluene and xylene) most of which are air toxics.

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2. Experimental setup

The experimental system is shown in Fig. 1. The test engine is a naturally aspirated, water-cooled, 4-cylinder direct-injection ISUZU diesel engine. Specifications of the engine are given in Table 1. The engine was coupled with an eddy-current dynamometer and engine operation was controlled by the Ono Sokki diesel engine test system. An Engelhard CCX8772A diesel oxidation catalyst (DOC) was used for after-treatment of the exhaust gas.

Euro V diesel fuel was used as a baseline fuel in this study. Blended fuels containing 8.1%, 16.4%, 25% and 33.8% by volume fraction of DEA, corresponding to 3%, 6%, 9% and 12% by mass of oxygen in the blends, were prepared for the experiments. The blended fuels are named as DEA8, DEA16, DEA25 and DEA34 to reflect the DEA volume fractions. The properties of Euro V diesel fuel, DEA and the four blended fuels are given in Table 2. Compared to the Euro V diesel fuel, the blended fuels have lower cetane number and lower calorific value.

The gaseous species in the engine exhaust were measured using online exhaust gas analyzers. A heated flame ionization detector (HFID) was used for HC; a heated chemiluminescent analyzer (HCLA) for NO_x/NO; and non-dispersive infra-red analyzers (NDIR) for CO and CO_2; exhaust gas temperature was measured with K-type thermocouple. The gas analyzers were calibrated with standard gases and zero gas before each test. Unregulated emissions including formaldehyde, acetaldehyde, 1,3-butadiene, ethene, ethyne, propylene and BTX (benzene, toluene and xylene) were measured with an Airsense multi-component gas analyzer. The Airsense gas analyzer is an Ion Molecule Reaction mass spectrometer, which allows dynamic studies of gaseous emission in low concentration (Dearth, 1999; Villinger et al., 1993, 1996). Standard benzene, toluene, methanol and formaldehyde gases were used to calibrate the Airsense multi-component gas analyzer while the other unregulated gases were calibrated indirectly with information provided by the equipment supplier.

Particulate mass concentration was measured with a tapered element oscillating microbalance (R&P TEOM 1105), in which the main sample flow rate was 1.5 l/min and the inlet temperature was held at 47 °C. The exhaust gas from the engine was diluted with a Dekati mini-diluter before passing through the TEOM. The application of the Dekati mini-dilutor and the TEOM for particle measurement has been covered in the literature (Patashnick and Rupprecht, 1991; Wong et al., 2003). The dilution ratio was determined from the measured CO_2 concentrations of background air, undiluted exhaust gas and diluted exhaust gas. The measured dilution ratio varied from 6.15 to 6.5 in this study.

Experiments were performed at the rated torque speed of 1800 rev/min, and at engine loads of 28, 70, 130, 190 and 240 Nm, corresponding to the brake mean effective pressures of 0.08, 0.20, 0.38, 0.55 and 0.70 MPa, respectively. Before each measurement, the engine was warmed up until the cooling water temperature reached 80–85 °C while the lubricating oil temperature reached 103–117 °C, depending on the engine load. All the gaseous emissions and particulate mass concentrations were continuously measured for 5 min at the exhaust tailpipe of the diesel engine and the average data were used for the analysis. Each test was repeated three times to ensure that the results are repeatable within the experimental uncertainties. The experimental uncertainty and standard errors in the measurements are shown in Table 3, which have been determined based on the method of Kline and McClintock (1953).

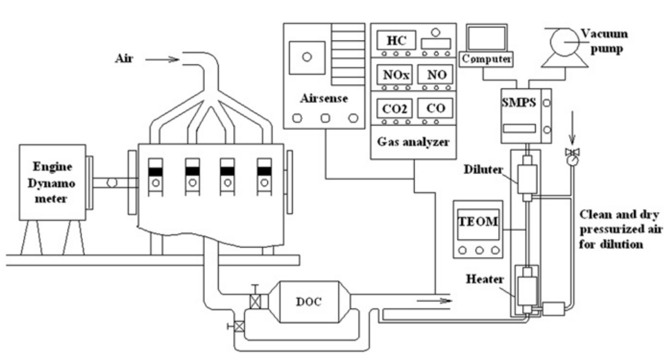

Fig. 1. Schematic diagram of experimental setup.

Table 1
Specifications of the test engine.

Model	Isuzu 4HF1
Engine type	4-cylinder, in-line, natural-aspirated
Maximum power (kW/rev min^{-1})	88/3200
Maximum torque (Nm/rev min^{-1})	285/1800
Bore × stroke (mm/mm)	112 × 110
Displacement (cm^3)	4334
Compression ratio	19.0:1
Fuel injection timing (BTDC)	8
Injection pump type	Bosch in-line type
Injection pressure (MPa)	18.1
Injection nozzle	Hole type (with 5 orifices)

3. Results and discussion

3.1. Engine performance

Table 4 shows the fuel consumption, the brake specific fuel consumption (BSFC) and the brake thermal efficiency (BTE) for each fuel at each engine load. In the experiments, the volumetric flow of the fuel was measured and then converted into the mass consumption rate based on the density of each fuel. Based on the mass consumption rate of the fuel, the lower heating value of the fuel and the engine torque, the BSFC and the BTE can be calculated. In general, there is a decrease in BSFC with increasing engine load from 0.08 to 0.55 MPa, while a slight increase at the highest engine load of 0.70 MPa. At 0.55 MPa, the BSFC of Euro V diesel fuel is 236 g/kW h, which increases to 246 g/kW h for DEA8 and 270 g/kW h for DEA34. The higher BSFC for the blended fuels is mainly due to the lower calorific value of DEA in comparison with that of the diesel fuel, thus more fuel is needed to maintain the same power output when the blended fuel is in use.

For each fuel, the BTE increases with engine load from 0.08 to 0.55 MPa, while it drops slightly at 0.70 MPa. Compared to Euro V diesel fuel, the BTE of the blended fuels increases slightly for the engine loads of 0.20–0.70 MPa, while at the engine load of 0.08 MPa, there is very minor difference between the different

Table 2
Properties of Euro V diesel fuel, DEA and blended fuels.

Property	Euro V	DEA	DEA8	DEA16	DEA25	DEA34
DEA volume fraction (%)	–	–	8.1	16.4	25.0	33.8
DEA mass fraction (%)	–	–	9.5	18.9	28.4	37.9
Lower heating value (MJ/kg)	42.5	25.5	40.9	39.3	37.7	36.1
Density (kg/m^3)@20 °C	840	1005	855	870	855	900
Boiling point (°C)	210–235	127	–	–	–	–
Cetane number	>51	15	–	–	–	–
Heat of evaporation (KJ/kg)	250–290	295.1	–	–	–	–
C (wt.%)	86	59.4	83.5	81.0	78.4	75.9
H (wt.%)	14	8.9	13.5	13.0	12.6	12.1
O (wt.%)	0	31.7	3	6	9	12