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Reducing CO_2 footprint through synergies in carbon free energy vectors and low carbon fuels

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ABSTRACT

Carbon-footprint from transport and power generation can significantly be improved when carbon free or reduced carbon energy carries are utilised that are compatible with the current technology of the internal combustion (IC) engines. The current study focuses on the reduction of diesel engine CO_2 emissions by improving ammonia and hydrogen combustion through the incorporation of alternative fuel, diethyl glycol diethyl ether (DGE) as an oxygenated fuel blend and combustion enhancer. The aim of the work is to study the potential synergies between DGE and two carbon free energy vectors H_2 and NH_3 in reducing the environmental effects and contribute in decarbonising internal combustion engines. DGE's ignition properties (i.e. high cetane number) improved the H_2 and NH_3 combustion efficiencies via counteracting their high auto-ignition resistances, and also contributing in lowering the unburnt H_2 and NH_3 emissions to the atmosphere. This led in the reduction of CO_2 by up 50% when 60–70% of diesel fuel is replaced with DGE, H_2 and NH_3. Synergetic effects were also found between DGE and the gaseous fuels (i.e. hydrogen and ammonia) simultaneously decreasing the levels of PM, NOx, HC and CO emitted to the atmosphere; thus mitigating the health and environmental hazards associated to diesel engines.

1. Introduction

Current worldwide transportation relies primarily on fossil fuels. Effective decarbonisation of the energy sector and especially transportation can be achieved by adopting fuel substitution with an energy carrier free of carbon. Ammonia (NH_3) and hydrogen (H_2) can be renewably resourced by utilising solar and wind energy. Hydrogen is believed to be one of the most potential alternatives [1] but due to its low volumetric energy density and infrastructure challenges associated with its transportation and handling, H_2 powered vehicles are still a niche product and widespread use is a long term goal [2].

Ammonia has been studied as an energy [3] and hydrogen carrier for fuel cells [4,5] and IC engines, providing that there is a process to split the NH_3 into N_2 and H_2 [6]. In recent work we have proposed that this is feasible through the application of the catalytic ammonia reforming and decomposition using the heat of the engine exhaust gas to drive the reactions [2]. The combustion of reformed gas, i.e. H_2, N_2, H_2O and unconverted NH_3, in diesel engine with diesel fuels has shown to reduce carbonaceous emissions, including CO_2. However, under a range of engine operating conditions, higher NOx emissions and incomplete combustion of the reformed gas was seen, similarly to LPG-diesel and natural gas-diesel dual fueled combustion, causing the production of other undesired emissions such as NH_3 slippage [7]. Combustion improvements were observed in a study of LPG-diesel and CNG-diesel fueled diesel engine with the use of a high cetane number fuel, such as diethyl ether (DEE, CN > 125) [8,9]. Most recently, Ryu et al. [10] investigated the compression ignition combustion of ammonia and dimethyl ether (DME, CN = 60), where several appropriate strategies and fuel/gas mixtures were shown for the use of ammonia in direct-injection compression-ignition engines. Apart from that, DME is also referred as a cetane enhancer blended with different fuels/fuel mixtures for the purpose of particulate emission [11].

Similarly, diethyl glycol diethyl ether (DGE) can be regarded as another potential combustion enhancer based on its high cetane (CN = 140) number and its high content of fuel-born oxygen. Because of its featured high ignitability, DGE combustion in a diesel engine has a shorter ignition delay and was demonstrated to burn

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sufficiently in low-temperature combustion regime under charge-gas dilution and cooling [12]. All these characteristics of DGE can lead to the engine out improved NOx/soot trade-off when it combusted with diesel fuel. Also as being similar to DEE, its presence (as fuel or fuel blend) in CI type of combustion is thought to be capable to assist the combustion of those less ignitable fuel alternatives, such as H_2 and NH_3.

In this work the impact of NH_3 and H_2 combustion on the CO_2 footprints of a diesel engine was studied. Following that, the addition of reduced carbon fuel, named DGE at different amounts into diesel, was studied as combustion improver of the carbon free gaseous fuels. The improvement in the properties of the diesel fuel (i.e. cetane number, ignition properties and presence of oxygen content) on the combustion and emission characteristics of the fuel mixture was assessed and compared in order to identify potential CO_2 and other environmental benefits.

2. Experimental

2.1. Test rig setup

The NH_3 reformate was simulated using NH_3 and H_2 gas bottles, whose flows were regulated by means of flow meters. The simulated gas additions were sent into the engine intake and premixed with the intake air. The liquid fuel (pure diesel or DGE blend) was injected into the cylinder to initiate the combustion. This approach required no modification to the fuel injection system. A Thringe Titan thyristor-type DC electric dynamometer was used to motor and load the engine.

2.2. Test engine

The engine is a single-cylinder, direct injection, naturally aspirated diesel engine. The main engine specifications are: bore 98.4 mm, stroke 101.6 mm, conrod length 165.0 mm, displacement volume 773 cm^3, compression ratio 15.5, maximum power 8.6 kW at 2500 rpm and maximum torque 39.2 Nm at 1800 rpm.

2.3. Data acquisition

The data acquisition and combustion analysis were carried out using in-house (University of Birmingham) developed Labview software. Output from the analysis of engine cycles included the in-cylinder pressure and rate of heat release (ROHR) at varying crank angle degrees, indicated mean effective pressure (IMEP), percentage coefficient of variation (COV) of IMEP values and other combustion characteristics.

2.4. Emission analysis

The gaseous emissions including NO, NO_2, N_2O, CO, CO_2, THC (C_1 based) and NH_3 were carried out by a MKS MultiGAS 2030 FTIR analyser (Fourier Transform Infrared Spectroscopy). Detection limits are 3.6 ppm for NO, 1.2 ppm for CO and lower than 1 ppm for the rest of gaseous species. Confidence intervals calculated using a 95% confidence level which reflects the reliability and repeatability of the equipment are shown in the results. FTIR results have been verified using known concentrations of CO_2, CO, NO, NH_3 and THC and a Horiba MEXA 7100DEGR (CO_2 and CO by Non-Dispersive Infrared, oxygen (O_2) by magnetopneumatic method, NO by Chemiluminescence Detection and HC by Flame Ionisation Detector) gas analyser was used to remove experimental bias during this procedure. Good agreement was obtained for the species and emission levels shown in this investigation. The hydrogen concentration in the exhaust was measured using a Hewlett Packard 5890 II gas chromatograph (GC) with thermal conductivity detector (TCD) using argon as carrier gas. An investigation of particulate matter (PM) was carried out using a TSI scanning mobility particle sizer (SMPS) 3080 electrostatic classifier to measure the particle size distribution. The sample was thermo-diluted using a rotating disk, with the dilution ratio set to 200:1 at 150 °C. Particulate measurement is focus on small particulates (in the range from 10 to 400 nm) being more dangerous for the environment and human health due to their higher reactivity, suspension time in the atmosphere and alveolar deposition fraction (especially ultrafine particulates lower than 100 nm).

2.5. Liquid fuel

Ultra-low sulphur diesel (ULSD) fuel was used as the primary liquid fuel for baseline operation. DGE was mixed volumetrically into the diesel to obtain the desired blends. Two blends with volumetric concentrations of 20 and 40% of DGE (DGE20 and DGE40 accordingly) were selected. This allowed a comparison between 3 different CN ratings and fuel-born oxygen contents. The fuel properties are listed in Table 1 for each tested fuel/fuel blend.

2.6. Test combinations of gaseous additions

In a previous on-board ammonia dissociation study using catalytic reforming technology [2], various amounts of hydrogen flow rates were produced under different reactor conditions. Unconverted NH_3, N_2 and H_2O (no NO_x production) make up the rest of the reactor product gas. For the purpose of current study, only H_2 and NH_3 were considered as the effective (combustible) reforming products; the obtained volumetric H_2 to reformate ($H_2 + NH_3$) ratio was ranging from 0.5 to 0.9, with roughly an increase of 0.1 from one reforming condition to another. Hence to simulate the reformate gas at higher flow rate, the observed H_2/reformate ratio was applied. The H_2 flows were chosen at 10, 15 and 20 l/min with various amounts of NH_3 selected accordingly to meet the actual H_2/reformate ratios. Pure forms of H_2 and NH_3 were also adopted for comparison purpose. All the H_2–NH_3 combinations are listed in Table 2.

2.7. Test procedures

The experimental runs were carried out in three separate sets for diesel and two DGE blends i.e. DGE20 and DGE40. All tests were performed under steady – state conditions at a controlled engine speed of 1500 rpm and a constant engine load of 5 bar IMEP throughout representing about 65% of full engine load at this engine speed. In all test sets, the liquid fuel blend was used to start and warm up the engine. Then different flows of NH_3 and H_2 or both combined were added into the air intake. The amount of liquid fuel injection was modified accordingly after the gaseous additions to keep the engine running at the same load. At least 20 min was allowed in each run for stabilising the engine before any of the readings being taken.

3. Results and discussion

3.1. Liquid fuel replacement

The liquid fuel replacements on mass bases by the same quantity of gaseous fuels was higher in the case of diesel fuel when compared to DGE-diesel blends as shown in Fig. 1. As the DGE content in the fuel blends was increased the amount of liquid fuel being replaced was reduced. This was due to the lower LHV (i.e. higher fuel-born oxygen content, Table 1) of DGE than that of diesel