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Biodiesel, emulsified biodiesel and dimethyl ether as pilot fuels for natural gas fuelled engines

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ABSTRACT

Dual-fuelling in compression–ignition (CI) engines is a mode of combustion where a small pilot injection of high-cetane fuel (i.e. diesel) ignites a premixed high-octane fuel (i.e. methane) and air mixture. This allows conventional CI engines to lower their emissions of smoke and nitrogen oxides (NO_x) while maintaining their high thermal efficiencies. However, poor ignitability of the main fuel–air charge results in increased emissions of unburnt hydrocarbons (HC) and carbon monoxide (CO). Conventional pilot fuels such as diesel and biodiesel (methyl esters transesterified from raw plant oil) have been researched extensively in prior work, showing that in terms of performance and emissions they perform fairly similarly. This is because the physical, chemical and combustion properties of various methyl esters are comparable to those of conventional diesel. In order to reduce these emissions of HC and CO, alternative pilot fuels need to be considered. As fuels employed during normal CI engine operation, both dimethyl ether (DME, a gaseous CI engine fuel) and water-in-fuel emulsions (conventional biodiesel mixed with varying concentrations of water) have shown that they reduce smoke and NO_x emissions significantly, while improving combustion quality. In this work, the performance of DME and water-in-biodiesel emulsions as pilot fuels was assessed. It was seen that the water-in-biodiesel emulsions did not perform as well as expected, as increased HC and CO emissions coupled with a mild change in NO_x levels was encountered (compared to conventional pilot fuel, in this case neat biodiesel). The emulsions performed very poorly as pilot fuels below a certain BMEP threshold. DME, while producing higher levels of HC and CO than neat biodiesel, managed to reduce NO_x significantly compared to neat biodiesel. Emissions of HC and CO, while higher than neat biodiesel, were not as high as levels seen with the emulsions. Thermal efficiency levels were generally maintained with the liquid pilot fuels, with the DME pilot producing comparatively lower levels.

1. Introduction

Concerns over climate change from use of fossil fuels and energy security are increasing. Fossil fuel reserves are finite, and trends of fossil fuel reserves to production ratio can be found in [1]. There are active research programs to reduce reliance on fossil fuels by the use of alternative and sustainable fuel sources, and thus to increase the time over which fossil fuels will still be available. One way to do this is to change how we use fossil fuels. For example, there is significant attention placed on producing a new generation of energy-conversion powerplants. The main focus has been on improving the three key parameters of powerplant performance; thermal efficiency, specific power and emissions [2–5]. While the basic measure of performance is thermal efficiency, there is an increasing need to extract more power from smaller powerplants [4,6–8]. Various options for increasing efficiency and power while reducing emissions are under investigation, for instance with water injection [9,10]. This same focus is applied to automotive engines, in particular compression ignition (CI) engines. This is because, as of 2008, CI engines form 30% of the current automotive fleet (which includes private and commercial vehicles) [11]. There is an ongoing effort to reduce smoke and particulate emissions from these engines, especially with the Euro 5 emissions standard coming into place in September 2009 [12]. Nitrogen oxides (NO_x) and particulate levels in automotive CI engine exhaust emissions are expected to drop by 30% and 80% respectively [12]. At the same time, Euro 5 unburnt hydrocarbon (HC) emission levels will remain at the current Euro 4 standard [12]. Currently, the quickest and cost-effective method to control these emissions is to treat the exhaust gas itself along the exhaust tract, before it is released to atmosphere. Particulate filters and selective catalytic reduction (SCR) devices have

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been used to reasonable success; however, there are issues with consistent, reliable operation across the operating cycle. Attention should be paid to reduce the production of undesirable emissions during the combustion process itself. The effect of different alternative fuels (all can be considered sustainable to different degrees) such as biodiesel (rapeseed methyl ester or RME) and dimethyl ether (DME) on the emissions production process has been investigated previously in various studies (for instance representative studies are published in Refs. [13–23]). In terms of exhaust emissions and overall performance biodiesel did not show much difference compared to diesel. As for DME, positive results in emissions reduction were encountered, as a result of a comparatively short ignition delay and increased mixing rates. However, engine operation with DME could not maintain the same power levels at medium to high loads as conventional fuels, due to its gaseous form and low combustion enthalpy.

In an effort to reduce emissions on a larger scale while maintaining power and efficiency levels, alternative fuelling strategies for CI engines have been considered. Generally, high-octane fuel combustion (seen in spark-ignition engines) produces lower smoke, unburned HC and carbon monoxide (CO) than high-cetane fuels. As a high-octane fuel cannot ignite under compression without an ignition source, a small "pilot" injection of high-cetane fuel is used to provide ignition. The high-octane fuel would provide most of the combustion enthalpy (more than 50%) while the pilot injection of high-cetane fuel would provide just enough energy to ignite the main fuel–air mixture. This mode of fuelling is called "dual-fuelling". Dual-fuelling in CI engines would allow the reduction of smoke and NO_x emissions common in conventional CI engine exhaust while maintaining the characteristically high CI engine thermal efficiencies. Different main (high-octane) fuels have been used, with natural gas and hydrogen gas in particular having been researched extensively [24–35]. These fuels were selected for their high octane number compared to gasoline (around 120 RON and 95 RON respectively). As a result they would be able to withstand the high compression ratio of a typical CI engine without knocking. Natural gas was selected as the main fuel in this work as it is fairly readily available, and is in relatively large supply compared to petroleum [1].

It has been shown that reductions in the targeted emissions (smoke and NO_x) can be achieved using the dual–fuel mode [25–27]. In fact they can be reduced by $\geqslant$ 90% and 20% respectively, depending on the type of pilot fuel employed. The low smoke emissions are due primarily to the higher hydrogen to carbon ratio of the high-octane fuel (compared to conventional high-cetane fuels) and a higher residence time for the fuel–air mixture to lean out after fuel injection [36]. NO_x reduction is due to lower combustion temperatures of dual–fuel operation, which stem from the slower burning velocity of natural gas [25,26]. However, dual-fuelling operation has significantly increased HC and CO emissions (by about 80% and 60% respectively) [25,26]. The pilot fuel ignition delay was also extended by about 3% as a result of a lower oxygen concentration in the intake charge as well as a higher specific heat capacity [25,26]. Emissions of HC and CO in particular indicate that ignition of the natural gas–air charge can be much improved, leading to more complete combustion.

Previous research [9,37,38] has found that, for normal engine operation, water-in-fuel emulsification lowers NO_x compared to neat fuels, while at the same time lowering smoke and particulate emissions. The reduction in NO_x levels stem from a phenomenon called "microexplosions" [9,38], where the water suspended in the fuel droplets vapourises thus cooling the combustion chamber charge. These microexplosions also result in the violent disintegration of the fuel droplet. This would allow a larger distribution of pilot fuel across the combustion chamber, giving a more homogeneous fuel–air mixture.

The physical and chemical properties of water-in-fuel emulsions depend significantly on how the emulsions are produced. In this work, water and fuel were mixed with a physical mixing device similar to a food blender. Other work [26,39] used different types of physical mixing devices such as an ultrasonic vibrating mixing tub. Chemical mixing with surfactants or mixing agents such as Span 80 and Tween 80 can also be used [40,41]. These different emulsifying methods can produce water-in-fuel emulsions with comparatively very different properties. For example, emulsion viscosities were observed to be similar to diesel in this case and in some of the literature [40]. Other work [39,40] however found that emulsions have up to three times the viscosity of diesel fuel. Therefore, the effects on engine performance and emissions can vary significantly with the different emulsions used. These effects on engine performance and emissions also vary with the operating condition, where different emulsions performed best at different engine speeds and loads [37].

DME, when used during normal fuelling, was found to produce similar emissions reductions [16]. However, due to its gaseous state as well as a significantly lower combustion enthalpy than diesel fuel, a larger amount of fuel needs to be injected in order to produce similar power as normal diesel fuel. Fuel consumption increased as a result. In fact, tests done at Queen Mary found that the engine frequently stalled at medium to high loads. In addition, it lacks the lubricating properties that is inherent in any liquid fuel. This would increase wear and tear in the engine, especially in the fuel pump and injector. As a pilot fuel for dual–fuel operation, it was seen that DME did not perform as well as liquid fuels (such as biodiesel and diesel) [25,26]. While apparently smoother combustion of the natural gas–air mixture was present, lower thermal efficiencies and increased unburnt HC as well as CO showed that DME did not ignite the charge as well as the liquid fuels. The same can be said about water-in-RME emulsified pilot fuels, where reductions in NO_x were modest compared to the increased unburnt HC and CO emissions [42]. Thermal efficiencies were higher than neat pilot fuels at certain conditions, implying that microexplosions still can positively affect the combustion process. It can then be generally concluded that while different pilot fuels managed to reduce the targeted emissions of smoke and NO_x, they did so at the expense of other emissions and thermal efficiency.

While different liquid pilot fuels have been investigated previously [31,43,44], work on gaseous and emulsified pilot fuels are lacking. In addition, there has not been a direct comparison of combustion and emission properties between these gaseous and emulsified pilot fuels. Here, a direct comparison was drawn between a gaseous pilot fuel (dimethyl ether or DME), two emulsified pilot fuels (5% and 10% water-in-RME emulsions) and biodiesel (RME). As diesel fuel performed very closely to biodiesel as a pilot fuel, we did not include it in the present investigation.

2. Experimental apparatus and procedure

A four-stroke single-cylinder Gardner 1L2 compression–ignition engine was used, the specifications of which is shown in Table 1. Fig. 1 illustrates the engine, hydraulic brake, fuel supply lines, various emission analysers and instrumentation.

In the dual–fuel tests, natural gas sourced from the building mains supply was plumbed directly into the inlet manifold, where it was inducted through a flow meter under the engine's own suction along with air. The amount of pilot fuel injected was fixed at a flow rate setting meant for 0.1 MPa brake mean effective pressure (BMEP) at both 1000 r/min and 1500 r/min during normal engine operation. The RME used were provided by Shell Global Solutions and supplied to the engine's standard fuel pump and injector via an auxiliary fuel tank. The DME entered the same fuel pump in a