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Combustion and emissions characteristics of a dual fuel engine operated on alternative gaseous fuels

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HIGHLIGHTS

- Natural gas and biogas were used as alternative fuels for a dual fuel engine.
- Dual fuel combustion caused rapid and high energy release rates.
- Ignition delay increased and combustion duration shortened during dual fueling.
- Lowest NO_x but sharply increased UHC emissions for all biogas–diesel operations.
- Substantial reduction in PM emissions for dual fuel engine operations.

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ABSTRACT

Among the different efforts towards the reduction in pollutant emissions from direct injection (DI) diesel engines, the use of gaseous fuels as a partial supplement for diesel fuel has been proposed by many researchers. An experimental investigation was performed to investigate the influence of dual-fuel combustion on the performance and exhaust emissions of a DI diesel engine fueled with natural gas (NG) and biogas (BG). The engine was operated at a constant speed of 1750 rpm and at two different loads: low (~3 N m) and high (~28 N m), which were about 10% and 85% respectively of the rated torque output of the engine at 1800 rpm. In this work, the combustion pressure and the rate of heat release were evaluated experimentally in order to analyze the combustion characteristics and their effects on exhaust emissions including particulate matter (PM) for single-fuel (diesel) and dual fuel combustion modes. In dual fuel mode, the peak cylinder pressure was found to be similar to diesel at 75% of the rated output of the engine. About 27–30% higher maximum net heat release rates were obtained for NG and biogas fueling respectively compared to diesel fueling. Longer ignition delays but shorter combustion durations were characterized for dual fueling operations. Specific NO_x emissions for dual fueling was always lower than diesel fueling case. Significantly lower specific PM emissions but sharply increased unburned hydrocarbons (UHC) emissions were measured for biogas–diesel dual fuel operations as compared to diesel fueling.

1. Introduction

The use of diesel engines as reliable and fuel efficient sources of power for the transportation of goods and people and for other critical needs of society including small capacity power generation, has steadily grown over the past century. In many cases they are preferable due to their high thermal efficiency, and low emissions of unburned hydrocarbons (UHCs), carbon monoxide (CO) and carbon dioxide (CO_2) compared to those of spark ignition engines [1,2]. The other important advantage of diesel engines is that they can operate at higher compression ratios, which permit them to use low energy-content alternative fuels such as biogas. However, diesel engines emit harmful pollutants including oxides of nitrogen (NO_x) and particulate matter (PM). That exhaust is of concern because of its impact on visibility and for its potential health hazards. Particulate emissions can be classified as potential occupational carcinogen and can have a number of other negative health impacts associated with exposure [3–6]. It is generally agreed that diesel engines used in transport systems represent an important source of ambient particulate matter [7]. These concerns are reflected in increasingly more stringent regulations to limit engine emissions. In response this, the manufacturers of diesel engines and refiners of diesel fuel have made revolutionary advances in

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diesel technology including improved engines, exhaust after-treatment and use of improved, ultra-low sulfur fuels. The PM concentration in newer engines is remarkably lower than in older engines as a result of these advances [8]. However, especially in poor and developing nations, the use of older diesel engines without any after-treatment facility will still be dominating and thus the blessings of new technologies will remain unattainable there. Therefore, the reduction of exhaust emissions from such older diesel engines is an ongoing concern that needs to be addressed.

Further, in recent years, fossil-fuels have suffered rises in prices because of the limitations of reserves, supply and considerable increases in demand resulting from industrialization. Again, this is also a growing concern for the developing nations as they expend a significant part of their national income to import petroleum products. Addressing the above concerns, researchers around the world are searching for alternative fuels for engines. Bio-fuels (oil and gas) have been subject to intensive research work globally because of their attractive behaviors in combustion and emissions [1,9].

Gaseous fuels in diesel engines operate in dual fuel mode where the main energy comes from the gaseous fuel (known as primary fuel) and the minimum amount of liquid fuel such as diesel (known as pilot fuel) acts as the ignition source. Biogas (BG) is a mixture of gases produced during the biological breakdown of organic matter in the absence of air. Being a renewable gaseous fuel, biogas has the potential to supplement the use of diesel fuel in engines that are used for transportation, irrigation and non-grid power generation purposes. This is especially important in the case of developing countries where meeting the growing demand of fossil fuels is a major economic challenge. The use of biogas has twofold benefits: it provides an alternative source of energy and protects the environment from the harmful greenhouse gas, methane (CH_4) that would otherwise be emitted into the atmosphere [10]. BG is composed mostly of CH_4 (50–70%) and CO_2 (25–50%), with low fractions of H_2 (1–5%), N_2 (0.3–3%), and hydrogen sulfide (H_2S) traces [11]. Natural gas can be considered as another alternative fuel for diesel engines as many parts around the world including developing nations have access to the reserves.

Numerous research works on experimental and theoretical investigations concerning the dual fuel diesel–natural gas operating mode have been reported over the last decades in the literature [12–18]. Combustion processes inside the combustion chamber as well as emissions characteristics of a dual fuel engine were reported in these studies. Ignition delay increased, first, on the addition of gaseous fuel compared with diesel fueling and reduced later with further gas addition. The combustion energy release for dual fueling can have three overlapping components: (i) pilot diesel combustion; (ii) gaseous fuel combustion in the immediate vicinity of the ignition and combustion centers of the pilot; and (iii) any preignition reaction activity and the turbulent flame propagation within the lean charge [12,13]. Significant reduction in NO_x emissions levels were possible by employing relatively advanced ~55–60° before top dead center (bTDC) pilot injection timings but with some penalty in UHC emissions and engine stability [15]. CO and UHC emissions were higher than corresponding diesel values for all conditions, particularly at low loads [12–15]. Combustion noise and cyclic variability strongly dependent on the type of gaseous fuels used and the fuel–air equivalence ratios in a dual fuel engine [16]. Lower emissions of NO_x and smoke were reported for methane than propane or butane in dual fueling [17]. Papagiannakis and Rakopoulos [18] showed that deterioration of the engine efficiency under diesel–NG dual fuel mode was evident at low and intermediate torques, while at high torque and high diesel supplementary ratios the engine efficiency improved. The authors also reported the increase of diesel fuel supplementary ratio resulted in reduced NO_x and soot emissions compared to normal diesel operation. Both CO and UHC emissions were observed higher than normal diesel operation, however, they were reduced at higher engine loads.

On the other hand, comparatively few research works on biogas–diesel dual fuel engines are found. The past investigations concentrated mainly on the performance and fuel consumption characteristics for biogas–diesel dual fuel engines. Combustion characteristics and performance and emissions analyses were performed by Karim and Amoozegar [19] and Karim and Weirzba [20] for a biogas–diesel dual fuel engine. However, their studies are mainly limited to part load or low load conditions. Mustafi and Raine [21] studied emissions from a dual fuel engine fueled with NG and biogas; however, dual fuel combustion characteristics and their effects on emissions were not presented there. Recent efforts using biogas–biodiesel in dual fuel application are found in Refs. [22,1,23], or biogas application in an HCCI engine [24]; where engine performance, combustion and emission characteristics are investigated. Although there are researches on the combustion and emission characteristics of biogas–diesel/biodiesel in dual-fuel concept, it is necessary to investigate in more detail characteristics of exhaust emissions and the combustion performance of these engines in order to establish biogas as an alternative fuel for stationary older diesel engines. The objective of this study was therefore to investigate the combustion characteristics of a diesel engine fueled with simulated biogas mixtures and natural gas, in dual fuel mode, and the influence of dual fuel combustion on the exhaust emissions, with special attention to the PM emissions. Natural gas was used here as a datum or reference fuel as its data are well established in the literature. All the results thus obtained, were compared between different engine fueling conditions.

2. Experimental setup and methodology

The experiments that form the basis of the results presented here were conducted in the Thermodynamics Laboratory, at The University of Auckland, New Zealand. The base engine for this research was a Lister Petter PHW1, single cylinder, four-stroke, direct injection (DI), stationary diesel engine. The major engine specifications are given in Table 1. The engine was modified to run on dual fuel mode and its original fuel injection system was maintained for the dual fuel operation. The engine modification for dual fueling, and all the required measurement systems including gaseous emissions and PM (gravimetric method); the properties of diesel and composition of pipeline NG etc. were described in detail elsewhere [21]. Compressed NG and CO_2 were mixed in volume basis in the laboratory to obtain simulated biogas mixtures such as BG1 (80% CH_4 and 20% CO_2); BG2 (67% CH_4 and 33% CO_2) and BG3 (58% CH_4 and 42% CO_2). The total experimental setup is presented in Fig. 1.

Cylinder pressure was measured by a Kistler 601A piezoelectric transducer connected to a Kistler 5011 charge amplifier. The engine crankshaft was equipped with a disk having 360 teeth on its circumference. A top dead center (TDC) detector close to the

Table 1
Engine specifications.

Engine type	Single cylinder, DI, water cooled
Bore/stroke	87.3/110 (mm)
Swept volume	659 (cm^3)
Connecting rod length	231.9 (mm)
Compression ratio	16.5
Injection timing at pump spill or start of injection	28°bTDC
Nozzle opening pressure	197–217 (bar)
Rated torque output (continuous)	32.6 (at 1800 rpm) N m