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Exhaust emissions characteristics of a multi-cylinder 18.1-L diesel engine converted to fueled with natural gas and diesel pilot

Mayank Mittal*, Ron Donahue, Peter Winnie, Allen Gillette

Generac Power Systems, Waukesha, WI, USA

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A six-cylinder, turbocharged and aftercooled diesel engine was converted to operate with natural gas and diesel pilot for generator application. The flow of natural gas was electronically controlled using a throttle valve, and it was pre-mixed with air before being introduced into the combustion chambers. The aim of this work was to study the exhaust emissions characteristics under diesel and dual fuel operations at different operating conditions. Exhaust emissions of total hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), soot, particulate matter and carbon dioxide were measured at different loads. This work also presents the effects of diesel oxidation catalyst on HC and CO conversions under dual fuel operation. Results showed that NO_x emission was reduced at all operating loads under dual fuel operation compared to diesel operation. HC and CO emissions were increased under dual fuel operation, but their concentrations were considerably reduced with oxidation catalyst. Contrary to conventional wisdom, it was found that soot and particulate matter were increased under dual fuel operation compared to diesel operation.

1. Introduction

Diesel engines are widely used based on their durability, cost-effectiveness and high torque. The primary advantages of diesel engines over spark-ignition engines are their improved fuel economy and resulting lower (approximately 20–30%) CO_2 emissions [1]. These improvements result from several factors, the most important being increased compression ratio and the fact that the diesel engines operate lean and unthrottled even at light load. In recent years, pollutant emissions from internal combustion engines have been significantly reduced. However, exhaust emission from diesel engines such as NO_x and particulate matter is still a serious concern. It is highly desirable to reduce these harmful pollutants. Moreover, fossil fuel consumption is steadily rising as a result of population growth in addition to improvements in the standard of living [2]. Therefore, low emission and energy conservation have focused attention towards developing relatively clean and efficiently burning fuels. Natural gas is one such fuel which burns cleaner compared to conventional liquid fuels like diesel or gasoline [3]. The use of natural gas is also motivated by lower fuel and maintenance costs, longer engine life and increased availability following developments in cryogenic technology to store and transport the fuel economically in liquefied form [4].

Natural gas is a gaseous fossil fuel consisting of various gas species, with methane as its main constituent (about 90% by volume) [5]. Fossil natural gas is found either together with other fossil fuels, e.g. crude oil in oil fields or with coal in coal beds; or on its own. The properties of natural gas are very similar to those of methane, which is its primary constituent. It is regarded as one of the most promising alternative fuels due to its chemical properties, with a high hydrogen-to-carbon ratio and high research octane number (about 130) [6]. Also, natural gas has relatively wide flammability limits and high auto-ignition temperature compared to diesel fuel. Based on fuel-air mixture preparation and ignition, natural gas could be used as: (i) single fuel (natural gas), homogenous mixture, spark ignited [7], (ii) high-pressure direct-injection of natural gas ignited by a glow plug or combustion of a diesel pilot. See, for example [8], for more details on this technique, and [9–11] on dual-fuel system design, or (iii) dual fuel (also known as bi-fuel or mixed fuel), homogenous mixture of natural gas and air, which is ignited by injection of a diesel pilot [12]. In dual fuel technology, natural gas is mixed with air before introduced into the combustion chamber. The gas-air mixture is then ignited by a liquid diesel pilot injection at the end of the compression stroke. Typically about

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* Corresponding author.
E-mail address: mmittal.28@gmail.com (M. Mittal).

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30% of the total fuel energy is supplied by the pilot fuel; however, this depends on various engine parameters, for example, operating load, intake manifold temperature, etc. Because of the homogenous mixture of air and natural gas, and compression ignition of the diesel pilot, dual-fuel engines have many features in common with spark-ignition engines and also share compression ignition (CI) characteristics. Compared to diesel engines, dual fuel engines could achieve much lower NO_x; however, they suffer from major increase in CO and HC emissions, particularly at light loads. Furthermore, since the fueling method has a homogenous charge, it is subject to knock [13].

Several studies have been reported on dual fuel engine technology. Karim [4] reviewed the combustion characteristics of the dual fuel engine. The author showed that the pilot ignition delay increases considerably with the addition of gaseous fuel, but then subsequently decreases with the addition of further gas. Varde [14] investigated the use of propane and natural gas as fuels for diesel engines. Balasubramanian et al. [15] investigated the performance of a small agricultural diesel engine under dual fuel operation. The authors showed the optimum specific energy consumption in dual fuel mode with 30% diesel pilot. Alla et al. [16] investigated the effect of pilot fuel quantity on the performance of an indirect injection diesel engine fueled with gaseous fuel. Diesel fuel was used as the pilot fuel and methane or propane was used as the main fuel which was inducted into the intake manifold to mix with the intake air. The authors showed that the low efficiency and excess emissions at light loads can be improved significantly by increasing the amount of pilot fuel, while increasing the amount of pilot fuel at high loads led to early knocking. Alla et al. [17] studied the effect of injection timing on dual fuel engine performance. It was found that the low efficiency and poor emissions at light loads can be improved by advancing the injection timing of the pilot fuel. Papagiannakis and Hountalas [18] investigated the characteristics of dual fuel operation in a single cylinder direct injection diesel engine. The authors concluded that dual fuel combustion using natural gas is a promising technique for controlling NO_x emission. Egúsquiza et al. [5] investigate the performance and emissions characteristics of a diesel engine operated within wide range of natural gas substitutions. The authors showed reduced NO_x emission under dual fuel operation over a wide range of operating conditions. However, under low loads, their results indicated high CO and HC emissions and a higher BSFC when compared to those of the corresponding diesel engine. Recently, Mahla et al. [3] investigated the effect of cooled EGR on performance and exhaust emissions characteristics of the dual fuel engine. The authors showed that 5% EGR is useful in improving the brake thermal efficiency under dual fuel operation, but higher EGR substitutions led to decrease in thermal efficiency. NO_x emission was reduced with EGR because of reduced oxygen and reduction in peak combustion temperature. However, smoke opacity was increased with increase in EGR substitutions. Elnajjar et al. [19] reported overall-generated noise for the dual fuel engine by measuring direct sound pressure levels. They found much higher sound pressure levels under dual fuel operation compared to diesel operation.

The aim of this paper is to study the exhaust emissions characteristics of a six-cylinder diesel engine operating under diesel and dual fuel operations at different operating conditions. The engine was modified to be suitable for dual fuel operation. Gas was inducted before the turbo assembly at low pressure. Emissions of total hydrocarbons (HC), CO, NO_x, soot, particulate matter and carbon dioxide are measured. The paper is organized as follows. Section 2 provides details of the experimental setup. The experimental results with discussions are presented in Section 3. Finally, conclusions are drawn in Section 4.

2. Experimental setup

The electromechanical system used in the present study was composed of a commercially available 18.1-L, six-cylinder compression-ignition engine, coupled with a generator rated at 600 kW electrical (kWe) power at full load. The engine used is a four-valve (two intake and two exhaust valves), direct-injection, turbocharged and aftercooled engine. It has a bore diameter of 145 mm and a stroke length of 183 mm. The technical specifications of the engine are listed in Table 1. A mechanically actuated electronically controlled fuel injector (MEUI) was used in each cylinder for direct-injection of diesel fuel. Common rail fuel injectors are generally used in a direct-injection diesel engine, but in recent years, MEUI injectors are also used because of their additional control capabilities via a first electrical actuator associated with a spill valve and a second electrical actuator associated with a direct operated nozzle check valve. The fuel injector was actuated via rotation of cam to move a plunger to displace fuel from a fuel pumping chamber either to a spill passage, or at high-pressure out of the nozzle outlet of the fuel injector for an injection event. In a typical design of mechanically actuated electronically controlled fuel injector [20], as the cam lobe begins to move the plunger, fuel is initially displaced at low pressure to a drain via the spill valve for recirculation. When it is desired to increase pressure in the fuel injector to injection pressure level (200 MPa in the present work), the first electrical actuator is energized to close the spill valve. When this is done, pressure quickly begins to rise in the fuel injector because the fuel pressurization chamber becomes a closed volume when the spill valve closes. Fuel injection commences by energizing the second electrical actuator to relieve pressure on a closing hydraulic surface associated with the direct operated nozzle check valve. The closing hydraulic surface of the directly operated nozzle check valve is located in a needle control chamber which is alternately connected to the pumping chamber or a low pressure drain by moving a needle control valve with the second electrical actuator. Interested readers may refer to [20] and references therein for more details on MEUI design and its operation.

Table 1
Engine specifications.

Parameter	Description
Number of cylinders and arrangement	6, in-line
Cycle	Four-stroke, compression ignition
Induction system	Turbocharged and aftercooled
Bore	145 mm
Stroke	183 mm
Compression ratio	14.5:1
Displacement	18.1 L
Rated net engine power and speed	652 kW, 1800 rpm
Diesel fuel injection system	Mechanical electronic unit injector
Diesel fuel injection pressure	200 MPa