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Gaseous and soot emissions characteristics of a 15.2-liter compression ignition engine operated with natural gas and diesel pilot

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Abstract:- The aim of this work was to study the exhaust emissions characteristics of a multi-cylinder, 15.2-liter diesel engine dual-fueled with natural gas at different operating conditions for generator application. The electromechanical system was composed of a commercially available six-cylinder turbocharged and aftercooled diesel engine, coupled with the generator rated at 500 kWe at full-load. Exhaust emissions of nitrogen oxides (NO_x), carbon monoxide (CO), total hydrocarbons (HC), soot 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. The results showed that NOx emission was reduced under dual fuel operation compared to diesel operation over a wide range of loads. HC and CO emissions were increased under dual fuel operation, but their concentrations were considerably reduced with oxidation catalyst. It was also found that soot emission initially increased with gaseous fuel percentage up to about 35 to 50 percent under dual fuel operation. However, further increase in gas percentage resulted in reduction of soot emission.

I. INTRODUCTION

The rapid depletion of conventional fuel resources and environmental awareness have focused attention towards developing economical and relatively clean burning fuels. Natural gas is one of the more established alternative fuels [1]. Most combustion systems are adaptable with relative ease to the use of natural gas for power production [2]. Natural gas as an alternative fuel is usable in both compression ignition and spark ignition applications. It has been used on a limited scale as vehicle fuel for more than 50 years [3]. In earlier years, the major motivation to use natural gas was economical: the lower cost of natural gas compared to diesel or gasoline. However, in recent years, attention has focused increasingly on environmental as well as economic benefits of natural gas. The use of natural gas is also motivated by longer engine life and increased availability following developments in cryogenic technology to transport the fuel economically in liquefied form. Natural gas is a gaseous fossil fuel consisting of various gas species with methane as its main constituent. Therefore, the properties of natural gas are very similar to those of methane. 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) [4]. Fossil natural gas is found in several forms: together with other fossil fuels, for example, crude oil in oil fields; with coal in coal beds; and on its own.

The focus of this work is on dual fuel technology, in which natural gas is mixed with air before being introduced into the combustion chamber. In this technology, the primary fuel (usually natural gas) is mixed with the air before being introducing into the combustion chamber, and ignited by a liquid diesel pilot injection at the end of the compression stroke. Typically about 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. Injected pilot fuel rapidly undergoes preflame reactions and ignites due to the heat of compression, as in a diesel engine [5]. The combustion of the diesel pilot then ignites the air-fuel mixture in the rest of the cylinder [6]. Because of the homogeneous mixture of air and natural gas, and compression ignition of the diesel pilot, dual-fuel engines have many features in common with both spark ignition and compression ignition engines. Compared to diesel engines, dual fuel engines can achieve much lower NO_x; however, they suffer from increased CO and HC emissions, particularly at light loads. Furthermore, since the fueling method is homogeneously charged, it is subject to knock [7]. Several studies have been reported on dual fuel technology; see for example [8-13]. However, most studies are limited to single-cylinder and/or gaseous emissions.

The objective of the present work was to investigate gaseous and soot emissions characteristics of a multi-cylinder, turbocharged and aftercooled diesel engine operating from low to high natural gas substitutions at different operating conditions. The gas was inducted in the intake manifold of the engine before the turbo assembly at low pressure. Emissions of nitrogen oxides, carbon monoxide, total hydrocarbons (HC), soot and carbon dioxide were measured at various operating conditions. The paper is organized as follows. Section 2 provides details of the experimental setup. Section 3 presents the experimental results with discussion. Finally, conclusions are drawn in Section 4.

II. EXPERIMENTAL SETUP

The electromechanical system used in the present study was composed of a commercially available 15.2-liter, six-cylinder compression-ignition engine, coupled with the generator rated at 500 kWe at full load. The engine used was a four-valve (two intake and two exhaust valves) direct-injection, turbocharged and aftercooled engine. It had a bore diameter of 137 mm and a stroke length of 171 mm. The technical specifications of the engine are summarized in Table 1. Experiments were performed at 1800 rpm engine speed over a wide range of loads. This commercial engine had been modified to operate under dual fuel operation; see Figure 1. The flow of natural gas was electronically controlled using a throttle valve, based on feedback from a differential pressure measurement across the orifice. The system was comprised of a gas flow meter; solenoid valves to shut off the gas when it was not desired or under diesel operation; pressure regulator; an actuator and throttle valve assembly to control the flow of natural gas. The gas was inducted before the turbo assembly at low pressure, about 21 inches of water. The gas-air mixture was then introduced into the combustion chambers for dual fuel operation. See Table 2 for natural gas composition used in this work [14]. Krohne and Sierra flow meters were used to measure the fuel flows of natural gas and diesel, respectively. A differential pressure transducer was used to detect the intake air pressure difference across the orifice to calculate the air flow. Temperature and pressure sensors were provided at various locations on this unit, for example, intake air, natural gas and diesel lines, inlet and outlet of the charge air cooler, exhaust outlet, etc. Resistive load banks were used to absorb the electrical load produced by the generator. An AVL emission bench AMA i60 was used for the gaseous emissions measurements. Soot emission was measured using an AVL Micro Soot sensor.

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	137 mm
Stroke	171 mm
Compression ratio	16:1
Displacement	15.2 liter
Rated gross engine power and speed	568 kW, 1800 rpm
Diesel fuel injection system	Mechanical electronic unit injector
Diesel fuel injection pressure	200 MPa

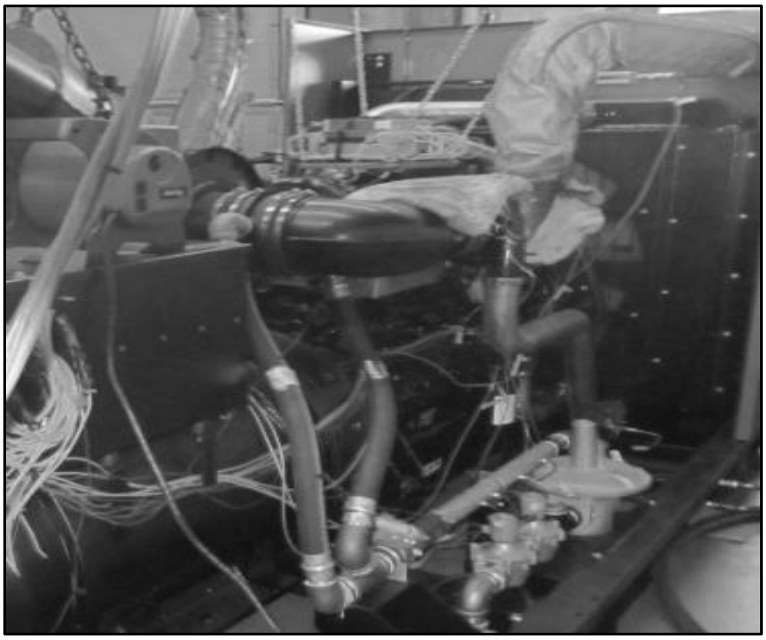

Figure 1. Experimental rig

Table 2: Natural gas composition

Component	Mol %
Methane	89.27
Ethane	3.88
Propane	0.48
n-Butane	0.06
Isobutane	0.04
n-Pentane	0.01
Nitrogen	3.94
Argon / Oxygen	1.82
Carbon Dioxide	0.46
Helium	0.02
Hydrogen	0.01
Higher molecular weight hydrocarbons	0.01

III. RESULTS AND DISCUSSIONS

Exhaust emissions characteristics of a 15.2-liter diesel engine dual-fueled with natural gas are presented. Experiments were performed at rated engine speed, i.e. 1800 rpm, over a broad range of loads. However, results are only presented at 135 kW (or 24% of full load), 325 kW (or 57% load), 413 kW (or 73% load), and550 kW (or 97% load) loads. Note that load percentage is defined based on rated engine power (see Table 1). At full electrical load, the generator provided the electrical power output of 500 kWe. At each operating load, gas percentage was increased from zero to maximum specified value while maintaining the same power output (or same engine speed and torque), and hence, the corresponding decrease in diesel pilot injection. The following expression was used to present the percentage of gaseous fuel [15]:

$$z = \frac{\dot{m}_{Natural\ \ gas}}{\dot{m}_{Diesel} + \dot{m}_{Natural\ \ gas}} \times 100\ (\%) \qquad (1)$$

where z = 0% represents the diesel operation (DO), and z > 0% represents the dual fuel operation (DFO). Its values vary from 0% to 75% depending on the operating load.

3.1 Effect of dual fuel operation on concentration of nitric oxides:

Figure 2 shows the variation of concentration of nitric oxides under diesel and dual fuel operations at 24%, 57%, 73% and 97% loads. As shown in the figure, the concentration of NOx was reduced under dual fuel operation compared to diesel operation at all operating loads. It is to be noted that under dual fuel operation, oxygen concentration decreases with the increase in gaseous fuel percentage, which replaces part of the intake air. Therefore, lower NOx concentration is expected under DFO compared to DO. At 24% load, NOx concentration was reduced from 267 ppm (z = 0%) to 125 ppm under DFO with z = 67%. The concentration of NOx was considerably reduced from 757 ppm under diesel operation to 201 ppm under dual fuel operation (z = 59%) at 73% load. At 97% load, NOx concentration under DO was 989 ppm. It was reduced to 671 ppm under dual fuel operation with z = 33%. The lower NOx concentration under dual fuel operation compared to DO is consistent with other researchers; see, for example, [16, 17].

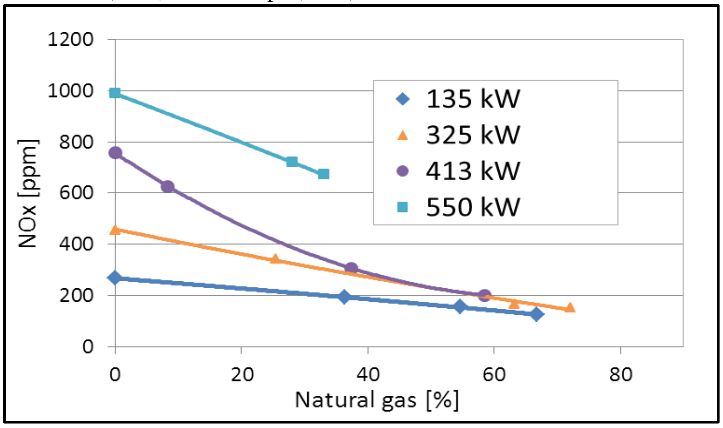

Figure 2. Variation of concentration of nitric oxides under diesel and dual fuel operations at different operating loads

3.2 – Effect of dual fuel operation on carbon monoxide concentration:

Figure 3 shows the variation of carbon monoxide concentration under diesel and dual fuel operations at 24%, 57%, 73% and 97% loads. The rate of CO formation is a function of unburned gaseous fuel availability and mixture temperature, both of which control the rate of fuel decomposition and oxidation [18]. It is evident that CO emissions under dual fuel operation were higher compared to DO at all operating loads. Furthermore, the concentration of CO emission was increased with the increase in gaseous fuel percentage. At light and moderate loads, the charge temperature is lower compared to higher loads, and the natural gas-air mixture in the cylinder is too lean to burn efficiently. The gaseous fuel utilization improves from moderate to high loads due to higher charge temperature. However, diesel engines tend to have relatively large crevice volumes, for example, the space between the side of the piston and the cylinder wall, and above the top ring [5]. Therefore, when a diesel engine is converted to dual-fuel operation, the larger piston land volume harbors a relatively large amount of unburned mixture and hence higher CO emissions. This is consistent with other researchers, such as Egúsquiza et al. [10]. These authors showed considerable increase in CO emissions under DFO compared to DO. Figure 3 also shows the effect of an oxidation catalyst on CO conversion. The concentrations of CO emission with catalyst were reduced to near zero level on both diesel and dual fuel operations at all operating loads.

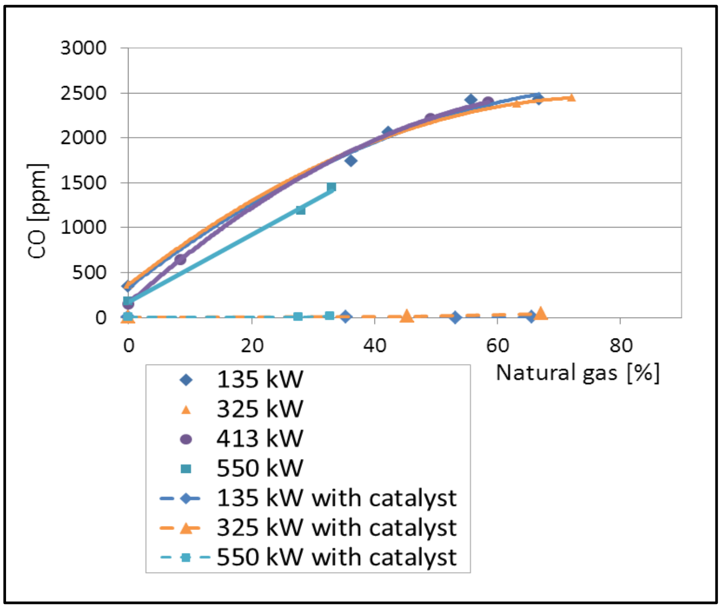

Figure 3. Variation of CO concentration under diesel and dual fuel operations at different operating loads

3.3 – Effect of dual fuel operation on concentration of hydrocarbons:

Figure 4 shows the variation of concentration of hydrocarbons under diesel and dual fuel operations at 24%, 57%, 73% and 97% loads. Hydrocarbons are the consequence of incomplete combustion of hydrocarbon fuel [18]. As shown in the figure, HC emissions were higher under dual fuel operation compared to diesel operation at all operating loads. This is consistent with the results of CO emissions. At 24% load (or 135 kW), hydrocarbons concentration was considerably high under dual fuel operation, i.e. 13521 ppm with z = 67%, compared to 45 ppm under diesel operation. This is mainly due to poor utilization of gaseous fuel, resulting in slower combustion. The natural gas-air mixture at light load is very lean, which complicates flame propagation throughout the combustion chamber from the pilot ignition. Note that the thermal efficiency at 24% load was reduced from 37.9% under DO to 26% under DFO (z = 67%). However, gaseous fuel utilization improves at higher loads. Hence HC emissions were reduced with increased load. HC concentration at 97% load was 26 ppm with z = 0%, and increased to 761 ppm under dual fuel operation (z = 33%). At this load, thermal efficiencies under diesel and dual fuel operations were 44% and 41.3%, respectively. As discussed earlier, the piston land volume harbors a large amount of unburned mixture, which contributes to the increase in HC emission under DFO compared to DO. Another source of higher HC emission under dual fuel operation is scavenging of the cylinder, resulting in unburned gas-air mixture blowing out to the exhaust. Figure 4 also shows the effect of oxidation catalyst on HC conversion. At light load, the oxidation catalyst was less effective on HC conversion due to lower exhaust gas temperature; however, this improved at higher loads due to increased exhaust gas temperature.

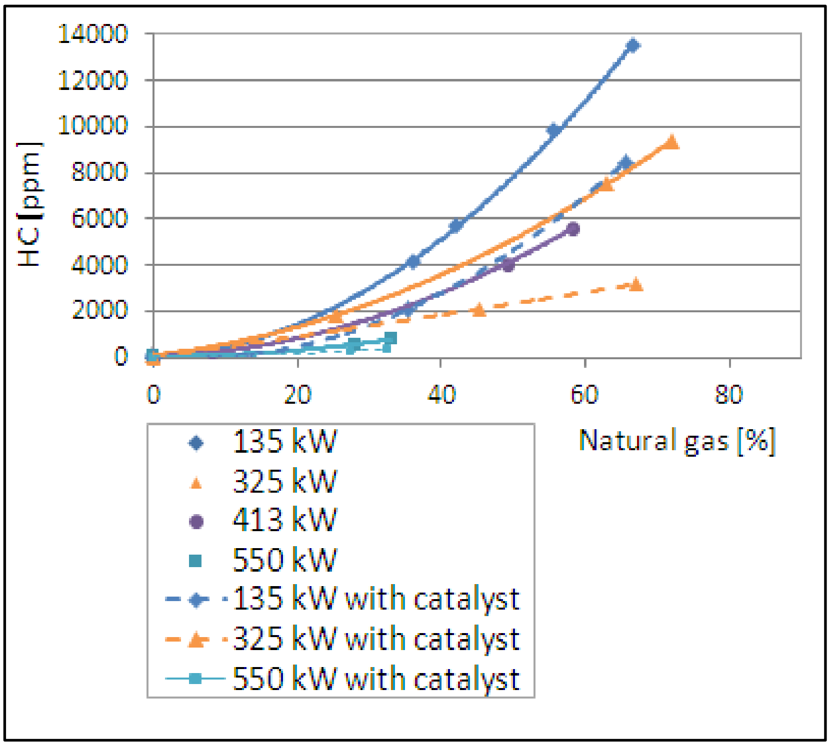

Figure 4. Variation of unburned hydrocarbons under diesel and dual fuel operations at different operating loads

3.4 – Effect of dual fuel operation on concentration of soot:

Figure 5 shows the concentration of soot under diesel and dual fuel operations at 24%, 57%, 73% and 97% loads. Under diesel operation, soot concentration was reduced with increased engine load. It was about 45 mg/m^3 at 24% load, and reduced to 4 mg/m^3 at 97% load. On the other hand, in the present work the concentration of soot was higher under dual fuel operation compared to diesel operation at all operating loads. At light load condition (or 24% load), soot emission was increased from 45 mg/m^3 under DO to 65 mg/m^3 under dual fuel operation with z = 67%. At a given gaseous fuel percentage, soot emission was decreased with increase in engine load. At 73% load, the concentration of soot was about 10 mg/m^3 under DO, and it was increased to 23 mg/m^3 under dual fuel operation (z = 59%). It is also evident that soot concentration first increased with gaseous fuel percentage up to about 35% to 50% at different loads, and then reduced with further increase in gas percentage. Sahoo et al. [19] also showed a slight increase in soot emission under dual fuel operation at 60% and 80% loads with low gaseous fuel mass ratios [20]. It was also shown that soot concentration reduces sharply at higher mass ratios of natural gas. However, it is to be noted that such high natural gas substitution ratios (over 80%) are not investigated in the present work.

At 97% load, soot emission was increased from 4 mg/m^3 under DO to 20 mg/m^3 under dual fuel operation with z = 33% (Figure 5). At high engine load and low percentage of liquid diesel fuel replacement, despite the slight improvement of gaseous fuel utilization, the concentration of soot formed is higher than the one under diesel operation due to lower cylinder charge temperature; see Papagiannakis et al. [17]. However, as the percentage of gaseous fuel increases, the reduction of soot emission becomes more evident [17]. This happens because the improvement of gaseous fuel utilization results in higher cylinder charge temperature during the expansion stroke, which eventually promotes soot oxidation rate and contributes to a decrease of soot concentration [17]. Experimental investigation in an optically accessible engine provides useful information on soot formation, which is beyond the scope of this paper. Furthermore, it is to be noted that the formation of soot is so complex that it is not yet well understood.

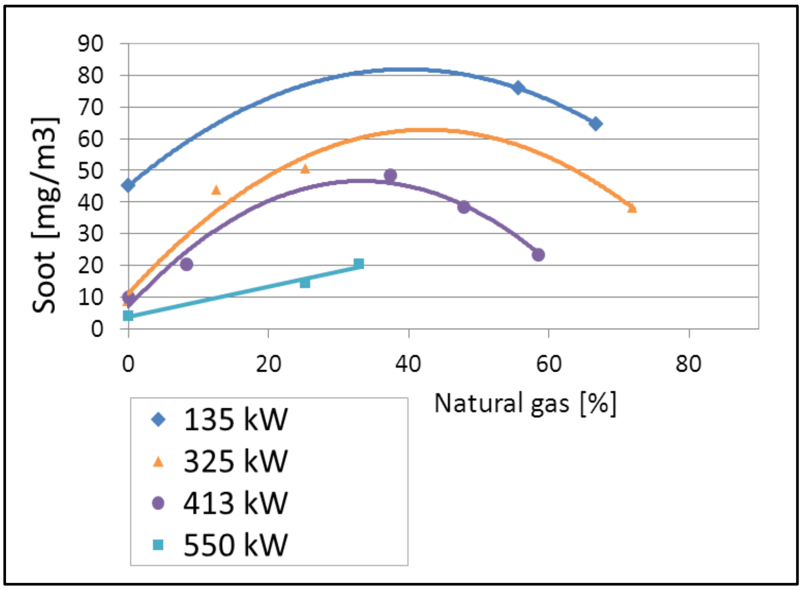

Figure 5.Soot emission under diesel and dual fuel operations at different operating loads

3.5 – Effect of dual fuel operation on concentration of carbon dioxide:

Figure 6 shows the concentration of carbon dioxide under diesel and dual fuel operations at 24%, 57%, 73% and 97% loads. It can be observed that the level of CO_2 emission was reduced under dual fuel operation compared to diesel operation. This is expected due to higher hydrogen-to-carbon ratio of natural gas than that of diesel fuel. At 24% load, the concentration of CO_2 was reduced from 6% under diesel operation to 5.1% under dual fuel operation with z = 67%. At 73% load, the concentration of CO_2 was about 8.7% under diesel operation, and it was reduced to 6.4% under dual fuel operation with z = 59%.

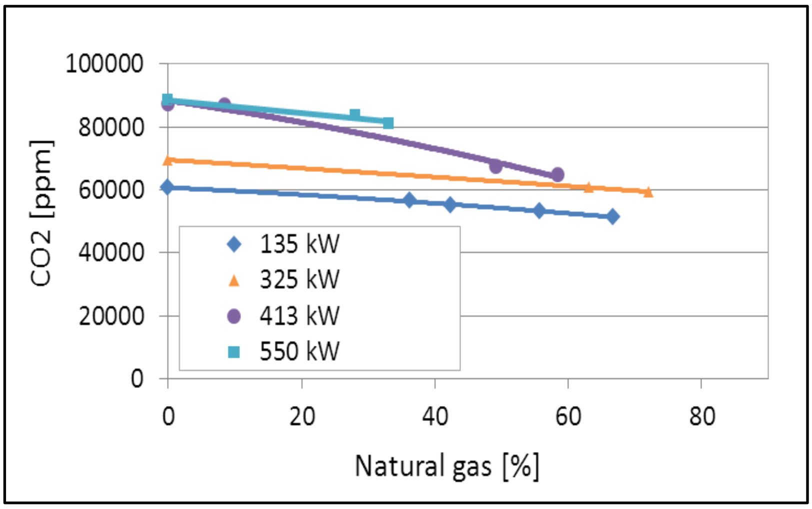

Figure 6. Concentration of carbon dioxide under diesel and dual fuel operations at different operating loads

IV. CONCLUSIONS

An experimental study was conducted to determine the gaseous and soot emissions characteristics of a diesel engine dual-fueled with natural gas at different operating conditions. The electromechanical system was composed of a commercially available 15.2-liter, six-cylinder diesel engine coupled with the generator rated at 500 kWe at full load. Gaseous emissions of nitrogen oxides, carbon monoxide, total hydrocarbons and carbon dioxide were measured at different loads. Soot emission characteristics were also investigated, from low to high natural gas substitutions at different operating loads. It was found that nitrogen oxides and carbon dioxide emissions were reduced under dual fuel operation compared to diesel operation at all operating loads. HC and CO emissions were increased under dual fuel operation, but their concentrations were considerably reduced using oxidation catalyst. Results also showed that soot emission first increased with lower gaseous fuel percentages at different loads; however, further increase in gas percentage resulted in soot reduction.

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