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Research Article

Performance and Emissions of a Dual-Fuel Diesel-LPG Engine Operating at Low and Medium Loads

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Abstract

Rural areas in Burkina Faso suffer from very limited access to electricity. In 2024, the rural electrification rate was estimated at 10.2%, compared to 87.8% in urban areas, for an overall national rate of 34.2%. Electricity generation using stationary diesel engines is a viable solution to address this disparity. Decentralized power generation facilities continue to face operating costs associated with diesel fuel and environmental concerns. In this context, the use of gaseous fuels such as Liquefied Petroleum Gas (LPG) or synthesis gas as the primary fuel in dual-fuel diesel engines could significantly mitigate this limitation. The objective of this study is to evaluate the overall performance and emissions of a Lister Petter diesel engine operating in dual-fuel mode at low and medium loads. The engine operated on diesel-LPG at a constant speed of 1,500 rpm under partial load. Specific fuel consumption in dual-fuel mode increased by 0.04 kg/kWh at low load compared to that of pure diesel, resulting in a maximum decrease in overall efficiency of approximately 2%. The two engine operating modes have comparable CO_2 emissions. However, the diesel-LPG mode emits more CO and reduces NOx concentrations in the exhaust gases by an additional 25%. A maximum decrease of 60 ℃ in the temperature of the exhaust gases was observed at medium load.

Keywords

Diesel Engine, Dual Fuel, LPG, Performance, Emissions

1. Introduction

The diesel engine is an internal combustion engine widely used in many sectors, including agriculture, transportation, industry, and electricity generation systems. It is robustly designed and suited for heavy-duty use, offering good energy efficiency. As a result, diesel engines are found in most decentralized electricity generation applications. The widespread use of diesel engines has been accompanied by growing concerns regarding fossil fuel consumption and greenhouse gas emissions, which contribute to environmental degradation and climate change [1-3]. Given the widespread use of diesel engines, the search for alternative solutions aimed at improving performance while reducing the environmental impact of diesel engine exhaust has become a major challenge.

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One promising approach is the use of diesel engines in dual-fuel mode. Diesel fuel, used as a pilot fuel, is combined with a gaseous fuel that serves as the primary fuel. This effective operating strategy allows for the respective advantages of both fuels to be leveraged: diesel's self-ignition capability and the more environmentally friendly combustion of gas [4]. Several studies have shown that this operating mode results in a significant reduction in diesel fuel consumption as well as in particulate matter and nitrogen oxide emissions, although under certain conditions, an increase in the concentration of unburned hydrocarbons and carbon monoxide may be observed in the exhaust gases released into the environment [5, 6]. The most used gaseous fuels in dual-fuel diesel engines are hydrogen, methyl diesel, syngas, biogas, natural gas, and liquefied petroleum gas (LPG). These gases have been the subject of several studies [1, 2, 7-14]. Natural gas and LPG are the easiest-to-use and most accessible gaseous fuels. Numerous studies on liquefied petroleum gas as the primary fuel in diesel engines have shown a significant reduction in particulate matter and smoke emissions compared to engines running on conventional diesel [12, 14-17].

Furthermore, the behavior of diesel engines in dual-fuel mode remains complex and highly dependent on operating conditions. Researchers [1, 5, 12, 13, 17-19] have reported a decrease in specific fuel consumption and a slight improvement in efficiency, along with more environmentally friendly pollutant emissions.

In the context of Burkina Faso, a sub-Saharan country where access to electricity is limited, particularly in rural areas. In 2024, the country's electricity access rate stood at 34.2%, with only 10.2% in rural areas [20]. To reduce the imbalance and disparity in the population's access to electricity, Burkina Faso has launched several rural electrification projects and programs, including the PTFM multifunctional platform program [21]. The multifunctional platform and several other types of energy-generation applications in rural areas rely on the Lister Petter diesel engine. Operating this engine in dual-fuel mode could improve the sustainability of these off-grid energy systems while ensuring clean and reliable electricity generation. The objective of this study is to evaluate the overall performance and emission characteristics of a Lister Petter diesel engine operating in dual-fuel (diesel-LPG) mode with a view to optimizing decentralized energy production applications using alternative gaseous fuels. This study also aims to address the lack of data on this type of diesel engine operating in dual-fuel mode.

2. Materials and Methods

2.1. Experimental Setup

The experimental study was conducted on a Lister-Petter TR1 engine, a single-cylinder, four-stroke, direct-injection, naturally aspirated, air-cooled engine. The engine drives a generator with a rated power of 6 kW at 1500 rpm, which delivers three-phase current. The engine's intake manifold was modified to operate in dual-fuel mode. The engine is equipped with a data acquisition system consisting of pressure and temperature sensors and flow meters, supplemented by a Testo 350 portable exhaust gas analyser. Cylinder pressure is measured using an AVL GH15D piezoelectric sensor inserted into the cylinder head, coupled to an AVL FI PIEZO charge amplifier. A Heidenhain ROD 426 rotary angle encoder, integral with the engine's camshaft, is used to determine the piston's angular position. Engine load control is managed by a modular resistor bank thermally protected by a 50 W fan. The loads tested range from 20% to 70% in 10% increments. The data acquisition system is based on a compact National Instruments (NI) chassis equipped with specialized modules. The system centralizes signals from the various sensors to a computer running in a LabVIEW environment, which provides real-time control and monitoring of engine data. The overall architecture of the test bench is illustrated in Figure 1.

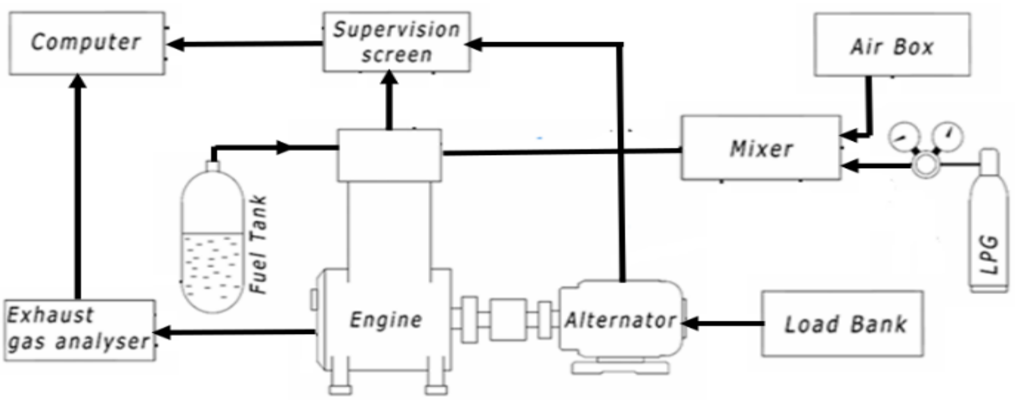

Figure 1. *Schematic diagram of the experimental setup.*

2.2. Device for Measuring Air and Fuel Flow Rate

The air flow rate is measured by a pressure-reducing device consisting of an 18-mm-diameter diaphragm installed at the air inlet of the chamber. The diaphragm is connected to a differential pressure sensor. Measuring the pressure drop across the diaphragm allows the air flow rate to be calculated using Equation (1).

$$\dot{m}_{air} = \alpha \cdot S_d \cdot \sqrt{2 \cdot \rho_0 \cdot \Delta P} \tag{1}$$

Where α is the flow coefficient, S_d the cross-sectional area of the diaphragm, ρ_0 the density of ambient air, and ΔP the pressure difference between the upstream and downstream sides of the diaphragm.

Figure 2 provides an overview of the air flow measurement system.

Figure 2. *Air flow measurement system: The air chamber is on the left and the sensor is on the right.*

The flow rate of the pilot diesel fuel was measured using a device consisting of a graduated glass column and a timer. At the base of the glass column is a "T" valve connected to the tank, which controls the flow of diesel fuel. When the valve is closed, the diesel fuel consumed by the engine comes exclusively from the graduated glass column. A stopwatch is used to measure the time it takes for a given volume of diesel to flow through the system.

1 : Device for measuring diesel pilot fuel

2 : Gaseous Fuel Mass Flow Controller

Figure 3. *Fuel flow measurement system.*

The engine's gas supply is provided by a high-pressure liquefied petroleum gas (LPG) cylinder connected to a mass flow controller (MFC). At the MFC outlet, the LPG is mixed with air before reaching the intake manifold. The LPG used contains approximately 80% butane and 20% propane by volume. Figure 3 illustrates the fuel flow measurement system.

The specific fuel consumption and overall efficiency were computed using Equations (2 and 3)

$$C_S = \frac{\dot{m}_{D/DF} + \dot{m}_{gaz/DF}}{P} \tag{2}$$

$$\eta_{grobal} = \frac{3600}{C_S \times LHV} \times 10^3 \tag{3}$$

C_S is the specific fuel consumption in kg/kWh, P is the engine's effective power in kW, $\dot{m}_{D/DP}$ the mass flow rate of diesel in pure diesel mode, $\dot{m}_{D/DF}$ the mass flow rate of diesel in dual-fuel mode, η_{global} is the engine's overall thermal efficiency, and PCI is the lower heating value of the fuel used.

2.3. Exhaust Gas Analyzer

Exhaust gases are analyzed using a Testo 350 portable exhaust gas analyzer, which employs electrochemical and infrared sensors. It consists of an analysis unit, a filter, and a Bluetooth control unit. Its configuration allows for the measurement of the following gases: O_2, CO, CO_2, NO, NO_2, and SO_2 at high temperatures. Figure 4 shows the installation of the Testo 350 gas analyzer probe on the exhaust gas outlet line.

Figure 4. *Experimental setup of the TESTO 350 gas analyzer probe.*

The probe isolates a portion of the exhaust gases, which is then dehydrated before being analysed. Emissions of NOx ($NO+NO_2$), CO, SO_2, and residual oxygen (O_2) are measured by electronic sensors called measuring cells. Carbon dioxide (CO_2) is measured by infrared (IR) radiation adsorption using an IR CO_2 sensor. The measurements are recorded using the testo EasyEmission SP3 software installed on a computer. For each test run, once the data has stabilized, the measurement is taken over a period of three (3) minutes with a sampling interval of five (5) seconds. The values are then averaged to obtain the concentration corresponding to each measured gas. Table 1 provides the technical specifications of the Testo 350 gas analyzer used for the measurements.

Table 1*. Technical Specifications of the Testo 350 Gas Analyzer.*

Measured Parameter	Range	Accuracy	Resolution
CO (ppm)	0 –10000	(200 to 2000) ±5% ±10% (rest of range)	1
NO (ppm)	0 – 4000	(100 to 1999.9) ±5%	1
NO_2 (ppm)	0 – 500	(0 to 99.9) ±5	0.1
CO_2 (%. V/V)	0 – 50%V	(0 to 25) ±0.5	0.01

2.4. Experimental Procedure

The tests were conducted at a constant speed of 1,500 rpm, with the engine load gradually varying from 20% to 70%. Data from operation on conventional diesel served as a reference for the analysis of combustion and emissions from the engine running on diesel-LPG. The test protocol is detailed in Table 2.

Table 2*. Experimental design.*

Engine Settings	Operating Mode	Fuel	Designation	Equivalence Ratio
Speed: 1500 rpm Injection timing: 20 ◦CAD BTDC Load: 20 to 70% Diesel substitution rate: 0 to max	Conventional Diesel	Neat Diesel	Diesel	0.28 to 0.57
	Dual fuel	Pilot: Diesel Main fuel: LPG	Diesel-LPG	0.35 to 0.59

3. Results and Discussion

3.1. Fuel Consumption

Diesel fuel is gradually being replaced by LPG. The fuel flow rates and maximum amounts of diesel replaced, based on engine load, are summarized in Table 3.

Table 3*. Fuel flow rates at the diesel substitution limit for different engine loads on Diesel-LPG.*

Load (%)	20	30	40	50	60	70
Diesel flow rate (kg/h)	0,16	0,19	0,23	0,27	0,32	0,35
LPG flow rate (kg/h)	0,4	0,38	0,41	0,43	0,45	0.5
Diesel Substitution (%)	61,7	58,9	60,3	59,6	58,8	57,9

These results indicate that the maximum diesel substitution rate remains generally consistent across all the loads studied, although a slight downward trend becomes apparent as the load increases. Fuel substitution by LPG is limited to approximately 60%. This rate is lower than the limits reported in the literature for diesel engines operating in dual-fuel mode with other alternative gaseous fuels. This limitation is explained by the fact that a large influx of LPG alters the combustion process, causing ignition delays and knocking [14, 22-24]. Furthermore, the low cetane number of liquefied petroleum gas reduces its chemical reactivity, which increases the auto-ignition delay and accentuates cyclic dispersion [25, 26].

The variations in diesel mass per cycle for the loads examined as a function of LPG mass are illustrated in Figure 5.

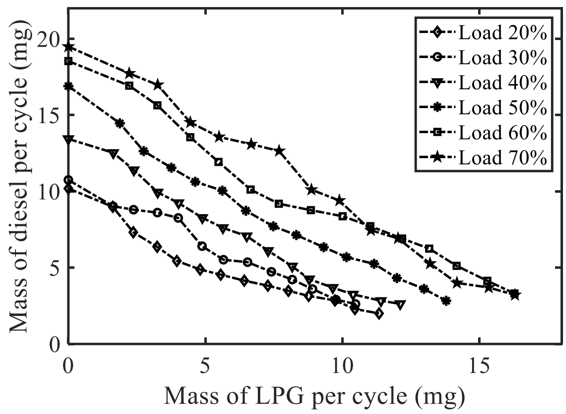

Figure 5. *Variation in the mass of diesel per cycle as a function of the mass of LPG.*

In dual-fuel mode, engine performance and emissions at low and medium loads are strongly influenced by the amount of pilot fuel injected [27]. The mass of diesel fuel consumed per cycle increases as the load increases. It rises from 5.54 mg/cycle at 20% load to 11 mg/cycle at 70% load. An increase in load requires a significant energy input, leading to higher fuel consumption. At a constant load, the amount of pilot fuel decreases continuously as the mass of gaseous fuel increases. This linear variation in the mass of pilot fuel as a function of the mass of gaseous fuel indicates that engine efficiency is only slightly affected by the substitution. However, engine operation in diesel-LPG mode remains subject to uncontrolled self-ignition (knocking) of a portion of the air-LPG mixture during the propagation of the flame front initiated by the pilot fuel. One of the causes of knocking is the increase in the proportion of LPG in the fuel mixture. Furthermore, LPG's low cetane number increases cyclic dispersion, limiting the amount of LPG that can be used [14, 28-31].

3.2. Brake-Specific Fuel Consumption and Engine Efficiency

Specific fuel consumption decreases as the load increases for all engine operating modes. It is well established that an increase in load improves engine efficiency, leading to a decrease in specific fuel consumption. In diesel-LPG mode, specific fuel consumption is slightly higher than that obtained with pure diesel fuel due to the influence of gaseous fuels on the combustion process. Authors [32, 33] observed the same trends during the operation of a single-cylinder diesel engine in dual-fuel mode. In the present study, the highest specific fuel consumption values are obtained at low loads for all engine operating modes. These values decrease as the load increases. For all loads studied, specific fuel consumption with diesel-LPG is very slightly higher than that of pure diesel. At 20% load, there is a difference of approximately 0.04 kg/kWh, which is significantly reduced at medium loads. This is explained by the energy density of LPG, which is of the same order of magnitude as that of diesel. Figure 6 illustrates the variations in specific fuel consumption and overall efficiency as a function of load for two engine operating modes.

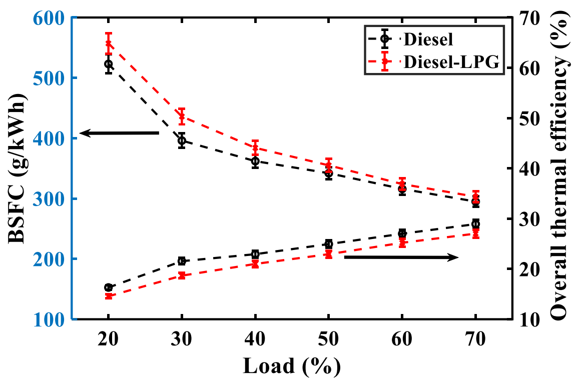

Figure 6. *Brake-specific fuel consumption and overall efficiency as a function of load.*

The engine's overall efficiency increases with load in all operating modes. Increased load improves the temperature and pressure conditions in the cylinder, leading to better combustion. In dual-fuel mode, efficiency is slightly lower than that of the engine running on pure diesel fuel. For all loads examined, the difference is less than 2%. This downward trend in efficiency is due to the ignition delay observed when the engine runs on diesel-LPG. However, the high calorific value of liquefied petroleum gas limits this reduction. Furthermore, the low carbon-to-hydrogen ratio of LPG improves flame temperature and results in more efficient combustion. Similar results were obtained in [14, 17, 18, 34-38].

3.3. Emissions

3.3.1. CO_2 Emissions

Figure 7 illustrates the CO_2 emissions of the two fuels for the different loads studied.

CO_2 emissions increase as the load increases across all engine operating modes. Consequently, the highest CO_2 concentrations are observed at high loads due to the increased amount of fuel admitted into the cylinder at these loads. CO_2 emissions are related to the fuels used and the quality of combustion. The higher the load, the more favourable the temperature and pressure conditions in the cylinder become for better combustion.

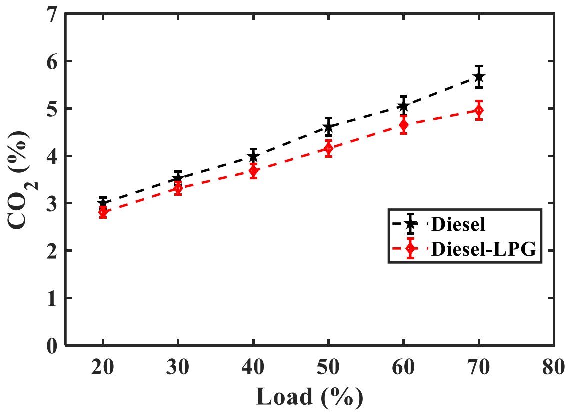

Figure 7. *CO_2 emission for the different fuels at different loads.*

The relative decrease in temperature in the combustion chamber of a diesel-LPG engine and the high hydrogen content of the gas account for the slight reduction in CO_2 emissions during dual-fuel operation [14, 39-41]. Looking ahead, the goal is to use synthetic gas in dual-fuel mode, as its combustion in the engine has no significant impact on CO_2 emissions. For biomass-derived fuels, CO_2 is considered part of the global carbon cycle, and its contribution to global warming is negligible [40]. However, from a Life Cycle Assessment perspective, certain forms of agricultural production (horticulture, highly mechanized farming, and crop-livestock integration) may have an unfavorable balance, leading to greenhouse gas emissions [42].

3.3.2. Carbon Monoxide (CO) Emissions

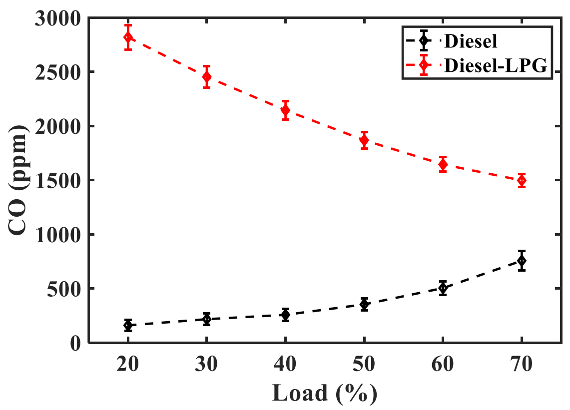

Figure 8. *CO emission for the different fuels at different loads.*

Carbon monoxide emissions are shown in Figure 8. CO concentrations in the exhaust gases for pure diesel and diesel-LPG modes vary inversely. The amount of carbon monoxide emitted from the combustion of pure diesel increases as the load increases. It rises from 161 ppm at 20% load to 760 ppm at 70% load. In dual-fuel mode, CO concentrations are higher. They decrease from 2,800 ppm at 20% load to 1,500 ppm at 70% load. The larger volumes of LPG admitted into the cylinder, as well as the lower temperatures observed at low load, are the factors that affect fuel decomposition and the oxidation of CO to CO_2 [18, 43-46].

3.3.3. Nitrogen Oxide (NOx) Emissions

Figure 9 illustrates the results of measurements of nitrogen oxide (NOx) concentrations.

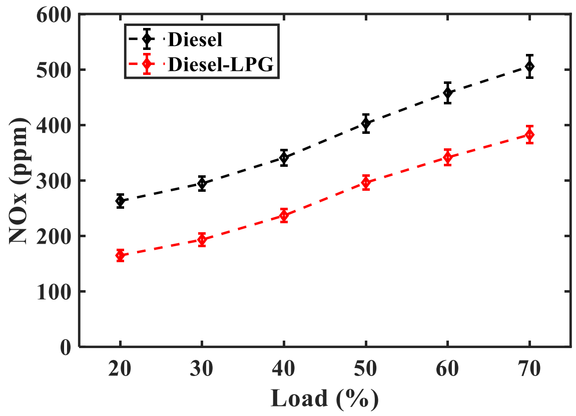

Figure 9. *NOx emission for different fuels at different loads.*

NOx concentrations vary with load across all engines operating modes due to the increase in combustion chamber temperature as load increases. Nitrogen oxides form primarily under high-temperature conditions in the presence of sufficient oxygen. Several authors [32, 43, 47-52] have reached similar conclusions.

In diesel-LPG operation, NOx emissions are lower compared to those observed when the engine runs on conventional diesel. Thus, at low load, there is a 38% reduction in NOx emissions in diesel-LPG operation compared to diesel. This difference decreases to 25% when the engine load is 70%. Increasing the proportion of LPG in the fuel mixture reduces pressure and temperature in the cylinder, resulting in lower NOx production in dual-fuel mode.

3.4. Exhaust Gas Temperature

Figure 10(a) shows the results of exhaust gas temperature measurements for the engine operating on pure diesel fuel and in dual-fuel mode under various loads, and Figure 10(b) shows the exhaust gas temperatures for the engine operating on diesel-LPG for various diesel substitution rates at 30% load.

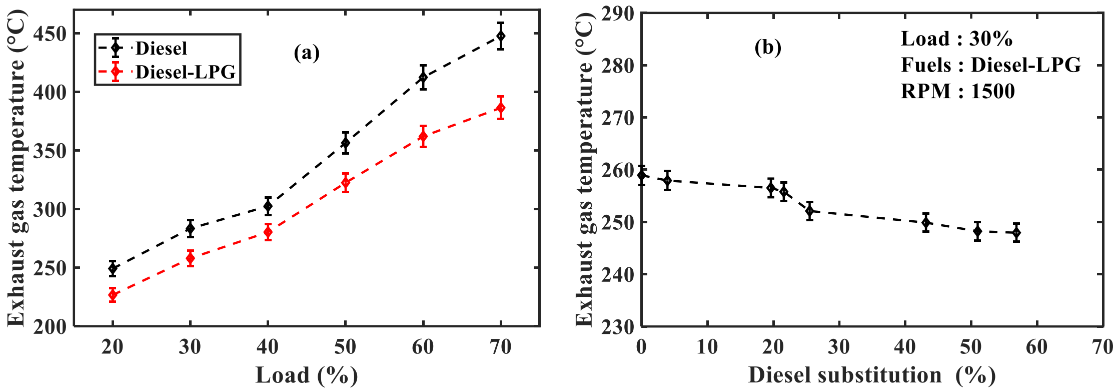

Figure 10. Exhaust gas temperature (a): as a function of load; (b): as a function of the diesel substitution rate at 30% load.

The engine's exhaust gas temperature increases with load in all operating modes. An increase in load leads to a rise in temperature within the combustion chamber, which contributes to improved combustion in the cylinder. Dual-fuel operation results in lower exhaust gas temperatures compared to those obtained with conventional diesel fuel. At 30% load, there is a 9% decrease in exhaust gas temperature for diesel-LPG. This reduction in exhaust gas temperature increases as the load increases, reaching 15% at 70% load. Regardless of the applied load, the exhaust gas temperature decreases as the amount of gas admitted into the cylinder increases in dual-fuel mode. The gaseous fuel affects combustion pressure. Maximum cylinder pressure decreases as the proportion of diesel is replaced by gaseous fuel. This leads to a decrease in combustion chamber temperature, resulting in lower exhaust gas temperatures during dual-fuel operation.

4. Conclusion

In this study, the Lister Petter diesel engine was operated in dual-fuel mode (diesel-LPG) at a constant speed of 1,500 rpm. The tests were conducted under light and medium loads. The main objective was to compare the engine's overall performance and pollutant emission characteristics during dual-fuel operation and conventional diesel operation, with a view to using synthetic gas from agricultural biomass for electricity generation. The results indicate a reduction in diesel fuel consumption in dual-fuel mode of approximately 60% for all loads examined. Specific fuel consumption is of the same order of magnitude for both operating modes, with a downward trend for diesel-LPG. It is higher at low loads and decreases linearly as the load increases. The lowest overall efficiencies are observed at low loads, increasing to 28.9% with pure diesel and 27.3% with diesel-LPG.

Carbon dioxide emissions are comparable to those of a conventional diesel engine, with a favorable trend for diesel-LPG. However, the diesel-LPG engine emits more carbon monoxide. Nitrogen oxide emissions are reduced by more than 25% in diesel-LPG mode. Exhaust gas temperatures in dual-fuel mode were lower than those of standard diesel for all loads studied. The introduction of LPG into the fuel mixture resulted in an 8% reduction in exhaust gas temperatures.

Operation of the Lister Petter engine in dual-fuel diesel-LPG mode yielded overall performance is like conventional diesel operation, with CO_2 emissions comparable to those of diesel, higher CO concentrations, and a significant reduction in NOx emissions. These results provide guidance for the study and optimization of synthetic gas combustion in the Lister Petter diesel engine.

Abbreviations

LPG	Liquefied Petroleum Gas
IR	Infrared
LHV	Lower Heating Value
MFC	Mass Flow Controller
NI	National Instruments
PTFM	Multifunctional Platform Program

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Author Contributions

Ali Diane: Conceptualization, Data curation, Methodology, Validation, Writing – original draft, Writing – review & editing

Yomi Woro Gounkaou: Conceptualization, Validation, Methodology, Writing – review & editing

Abdoul Rasmane Zangre: Conceptualization, Methodology, Validation, Writing – review & editing

Boubou Bagre: Validation, Writing – review & editing

Tizane Daho: Conceptualization, Methodology, Project administration, Validation

Antoine Bere: Project administration, Supervision

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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