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ORIGINAL ARTICLE

Experimental and numerical study of using of LPG on characteristics of dual fuel diesel engine under variable compression ratio

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Abstract In this work, an experimental and numerical investigation are carried out to study the impact of adding Liquefied Petroleum Gas (LPG) on the characteristics of diesel engine. New injection control system (ICS) is designed to manage an LPG injector on intake manifold a single-cylinder diesel engine. The engine test rig is powered with traditional diesel fuel to generate the base line data for comparison. Different conditions of load (0%, 25%, 50%, 75%, and 100%) in terms of brake power with three compression ratios of 14.5, 15.5 and 16.5 at constant engine speed of 1500 rpm. LPG is tested in four rates (5 L/min, 10 L/min, 15 L/min, and 20 L/min). The numerical analysis is performed with the help of Diesel-RK simulation software. The multizone combustion model is adopted. Same operating conditions in the experimental work are followed in the numerical simulation. The obtained results revealed that brake thermal efficiency (BTE) and exhaust temperature are reduced while brake specific fuel consumption (BSFC) is increased as the rate of LPG increased. Inducting LPG with (5,10,15,20) L/min reduced carbon monoxide (CO) by 16.6%, 14.7%, 20.3%, and 18.8% respectively. The maximum reduction in hydrocarbon emission (HC) is 8% at the rate of 15 L/min compared to diesel. The volumetric efficiency and NO_x emissions are decreased with the use of LPG. As the compression ratio increases, BTE increases and BSFC decreases because of increasing combustion temperature and pressure which decreases delay period, ignites fuel fast and produces more power in small time. The impact of increasing compression ratio

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reported significant reduction in, CO, HC while NO_x are increased. The experimental findings are compared to the results of the Diesel-RK software, as well as with the results of other researchers and good harmony among them is noticed.

1. Introduction

Diesel engines are now preferred in many industries because of their great economy, higher efficiency, lower HC and CO emission advantages and low fuel costs (Süleyman et al., 2021a; Süleyman, 2020b) Diesel engines provide a number of benefits, including high output, long life, minimal emissions of carbon monoxide, and a low cost of ownership. Regardless of the size of the vehicle, they are extensively used (Süleyman and Samet 2021). When compared to other engines, diesel (CI) engines improve in thermal efficiency, durability, and power output (Jothi et al., 2008). Combustion in diesel engines starts when fuel is injected into the cylinder at the end of the compression stroke. When diesel fuel is put into hot compressed air, it ignites due to the high temperature of the air. High pressure and temperature in the combination cause ignition (fuel–air) (Mollenhauer and Schreiner, 2010). International attention has been drawn to the problem of diesel engine exhaust emissions, which is still a major issue. As a result, it is essential to lower the quantity of NO_x in the exhaust stream in order to comply with environmental regulations. Based on the international "Kyoto protocol" decision for the reduction of greenhouse gas emissions and rapid decrease in fossil fuel reserves studies on new fuels and fuel technologies that can be clean, economical, and alternative to fossil fuels are accelerating (Samet et al., 2023) As a result, the development of an engine system that is both energy-efficient and environmentally friendly is critical. According to many studies, utilizing biodiesel generated from various feed stocks is essential since it has a significant influence on engine characteristics, including combustion, performance, and emission parameters (Suleyman et al., 2022; (Raju et al., 2020), Venu et al., 2020; Swamy et al., 2019). Many research has been conducted recently on alternative energy sources and the improvement of current systems due to the rising energy demand in the globe and the likelihood that the petroleum fuels used in motor vehicles will not be able to supply the demands in the near future (Stavinoha et al., 2000; Süleyman et al., 2020). Alternative fuels that may be utilized today are crucial for reducing our reliance on oil, but we also need to take into account the human activities, including production that can impact the environment (Süleyman et al., 2019).

Diesel engines that operate on alternative fuels including CNG, LNG, liquefied petroleum gas, dimethyl ether (DME), and hydrogen have recently been developed (Stavinoha et al., 2000). It is regarded as a cleaner fuel than diesel, and liquefied petroleum gas, often known as LPG, is one of the most popular and appealing gaseous fuels available (Rao et al., 2010). In the last ten years, there has been a fast increase in the development of cars that are powered by LPG. These vehicles are both inexpensive and environmentally friendly (Lee and Ryu 2005; Helin et al., 2006; Qi et al., 2007). For dual-fuel combustion, gaseous fuel is injected into the combustion chamber with air and compressed like in traditional engines (Ceviz et al., 2006; Lee et al., 2009; Saraf et al., 2009). It can operate on two different kinds of fuel simultaneously. During the suction stroke, the gas fuel (LPG) is injected along with the intake air. The higher (auto ignition temperature and octane rating) of LPG prevent it from burning during the compression stage; however, it is readily burned when combined with another fuel that has a low auto ignition temperature, such as diesel (Cernat et al., 2016). Compared to other types of fuel, LPG has a lot of benefits. The engine oil is not diluted by the gas, so it may be used for a longer length of time. The anti-knock qualities of petroleum gas are determined by its high cetane number. LPG has a larger calorific capacity than diesel, allowing for a greater engine output while using less fuel (Chaichan 2011). Sulfur is nearly nonexistent in petroleum gas. Using diesel fuel with gas increases the lifespan of an engine because it reduces sulphur dioxide emissions, which is a major benefit since that component is a catalyst for corrosion (Saleh 2008). More LPG injection increases performance and reduces exhaust emissions. With its low cetane number, LPG can only be used as a dual-fuel in diesel engines since it is difficult to utilize significant volumes of the fuel (Sinaga et al., 2019). There are several benefits to dual-fuel engines, including increased power and thermal efficiency, as well as reduced exhaust emissions and brake-specific fuel consumption compared to single-fuel engines (Ergenç et al., 2014; Murthy et al. 2021). In the last several years, researchers have conducted a number of fuel investigations. Performance is greatly affected by the use of dual fuel. LPG can enter diesel engine in one of two ways: one in a gaseous form where it is mixed with air in the air stream. The combination of LPG and air is pressurized in the cylinder in the same manner as a conventional diesel engine does. Because LPG has a greater temperature at which it may ignite on its own, the combination does not spontaneously ignite. Additionally, the standard diesel injection equipment only needs to inject a small amount of diesel in order to begin the combustion process. The second approach takes advantage of the liquid form, during which it is combined with diesel at a pressure that is above 5 bar as a result of the increased pumping pressure (Abd Alla et al., 2000; Ashok et al., 2015). When literature sources are examined, it can be seen that fuels containing oxygen generally improve combustion and increase BTE (Ashok et al., 2015). Several researchers have investigated the possibility of utilizing LPG as a fuel in compression ignition (CI) engines.

(Vezir et al.; 2011) tested the impact of LPG injection on a one-cylinder, normally aspirated diesel engine's characteristics. In order to identify the optimal LPG content for dual operation, an electronic LPG injection system should be used. On a mass basis, LPG introduced at rates of 5 to 25 percent. The researchers found a 15 % LPG mixture in combination with an engine speed of between 1400 and 1800 rpm provided the best results in terms of SFC and brake thermal efficiency.

The optimal LPG injection rate in terms of exhaust emissions and engine performance was determined to be 5%. (Le 2011) findings indicate that the maximum level of LPG replacement is achieved owing to the knocking limit when the engine is operating at full load and low speed. Despite dual-fuel engines' cost-effectiveness, it operated at greater speeds. At a speed of 2000 revolutions per minute, a level of 54% of LPG is obtained; at higher speeds, this level drops to 40%. (Kumaraswamy and Prasad 2012) operated the diesel engine in dual fuel mode with LPG and diesel. On the air intake side of the engine, an LPG carburetor is included for use with the engine operating on dual fuel. The microcontroller and a sensitive speed sensor are placed under the engine's flywheel. When the engine reaches 1000 rpm, the microcontroller will activate the solenoid valve of the LPG line. It opens, allowing LPG to flow through intake manifold. A test revealed that dual-fuel operation resulted in 15% higher braking power and 30% less brake specific fuel consumption compared to the diesel mode of operation. (Elnajjar et al., 2013) tested naturally aspirated, diesel engine for the performance effects of numerous LPG formulations starts from 100 percent propane to 100 percent butane with 15% percent step. The results demonstrated that although LPG composition has minimal influence on engine efficiency, it has a substantial impact on combustion levels of noise. Butane and propane alone are not as efficient as a blend of the two gaseous fuels. (Renald and Somasundaram 2012) used 60/40 LPG/diesel fuel combination increases diesel engine efficiency by 5% in both thermal and mechanical terms, while reducing specific fuel consumption and CO emissions by 33% and 13%, respectively. However, a blend of 40% diesel and 60 % LPG decreased NO_x and CO_2 emissions by a total of 35 % and 67% when compared to the original fuel. (Rosha et al., 2014) tested EGR effects on performance and emissions in a diesel/LPG dual-fuel engine with different loads. It was decided to test out the engine's 3.7 kW DI rating by using an air-cooled, constant-speed single-cylinder engine. LPG was decontaminated right before the input manifold to allow for a dual fuel system. Between the exhaust and intake pipes, the hot EGR system was inserted. The fuel consumption fell 8.75 percent and BTE improved by and 28.9 percent. (Vijayabalan and Nagarajan 2009) conducted tests on the performance, and emissions, characteristics of an LPG diesel dual-fuel engine employing a glow plug in a modified diesel engine. Compressed air and a little amount of diesel pilot spray ignited the principal fuel, LPG. There was a 2% improvement in brake thermal efficiency at 80% load, but there was no significant difference at full load. In the dual fuel mode with a glow plug, hydrocarbon (HC), carbon monoxide (CO), and smoke emissions were reduced by 69%, 50%, and 9%, respectively, compared to the dual fuel mode without a glow plug. Glow plug aided dual fuel mode has a peak heat release rate of 59.7 J/°CA. (Rimkus et al., 2016) used the AVL BOOST software to undertake both experimental testing and numerical simulations on a CI engine running in dual-fuel mode. It was tested with five LPG/diesel mixtures at 2000 rpm and 60 Nm brake torque. According to the experimental and numerical simulation results, the BSFC was lowest at 60 % LPG, while the highest engine efficiency was attained at 40 % LPG. (Giang and Son 2017) examined the performance and pollution of the Toyota diesel engine operating on dual-fuel LPG-Diesel. The torque and power of a dual-fuel engine were lower than in the case of 100% diesel, but not by a considerable amount. NO_x and smoke emissions drop in all operating modes, whereas CO and HC emissions rise significantly. (Yuvaraj et al., 2018) tested typical dual-fuel diesel engine using diesel and LPG. The subjects of this investigation are water cooling and direct injection in a single-cylinder diesel engine. The LPG injected to the manifold at a rate of 0.25 kg/h using the LPG valve and pressure regulator. emissions of CO, CO_2, HC, NO_x, and O_2 were reduced. Reducing CO_2 emissions as the load rises, the LPG-diesel mode's brake thermal efficiency improves by more than 3% over the pure diesel engine. Pure diesel consumes 0.8 kg/Kw.hr, but the mix fuel consumes 0.78 kg/kW.h. Emissions and performance of a dual-fuel engine operating on diesel fuel will be examined in this research by studying the effects of LPG injection into the cylinder during the intake phase. An optimal LPG rate for dual fuel operation is being studied in order to enhance the quality of the emissions.

An effort made by Suleyman S. et al. [1] to determine the optimum ratio of LPG to be used efficiently in terms of performance and emissions in a spark-ignition (SI) engine running on gasoline-LPG blends using response surface methodology (RSM). It was concluded according to the optimization results, the optimum factor levels were determined as 35% and 2400 W for LPG and engine load, respectively. According to the verification study, the maximum error between the experimental results and the optimization results was found as 3.75%. As a result, it is concluded that the SI engine fueled with LPG can be successfully modeled with low error rates by using RSM.

(Süleyman and Samet 2020) carried out experiments on single cylinder, SI engine with variable throttle position powered by gasoline, LPG, and biogas fuels in different volumetric percentages. According to the results, with the use of biogas and LPG in the full throttle mode, a 75.52% and 34.19% increase in the BSFC was determined compared to the use of gasoline, while a 16.04% and 8.95% reduction in the BTE was determined. On the other hand, with the use of biogas and LPG, a decrease of 15% and 62.03% in CO emissions, 23% and 63% decrease in HC emissions, 6.77% and 56.42% decrease in CO_2 emissions were detected compared to gasoline. In the half throttle mode, BSFC increased by 85.2% and 45.51%, while BTE decreased by 33.43% and 20.22%. In addition, a decrease of 15.97% and 47.65% on CO emissions, 21.19% and 62.38% HC emissions, 6.84% and 69.54% CO_2 emissions were detected.

From the previous studies it can be seen that most of the studies seen in the literature previously are based on experimental investigations, while this study is a combination of experimental and numerical investigation that will be done with the help of simulation software Diesel–RK. Additionally, there is no information (research study) in Iraq about the use of LPG with diesel in CI engines. This sparks an interest in investigating the use of LPG in diesel rather than petrol engines subjected to different conditions of load and compression ratio. The present work uses a new ICS is to manage the quantity of LPG injected into the intake manifold of the engine while the normal diesel fuel injection system still exists. The study aims to investigate how inducting different rates of LPG (5, 10, 15, and 20) L/min at different conditions of load (0 %, 25%, 50%, 75 %, 100%) with variable compression ratio impacts the characteristics of a single-cylinder dual fuel diesel engine.

2. Materials and techniques

In this study, LPG was employed as a gaseous fuel. It is inducted beside original diesel as an effort to minimize diesel engine emissions. Diesel engine testing rig has been converted to run on both diesel and LPG. Flow rates from 5 to 20 L/min step of 5 L/min are evaluated and compression ratio is changed from 14.5 to 16.5. Table 1 shows the properties of diesel and LPG fuels.

3. Experimental setup

One-cylinder, four-stroke, direct injection water-cooled diesel engine was employed to perform the tests. Specifications for the engine are shown in Table 2. Testing is done at the University of Babylon's Faculty of Engineering lab. A computerized data recording system and various sensors and instruments combined with a diesel engine and eddy current dynamometer. An illustration of the set-up may be seen in Fig. 1 and the real image for the experimental work is shown in Fig. 2. It's equipped with a CI engine test panel and an LPG system, for instance. The engine test rig is operated with two modes of operations. The first mode deals with testing pure diesel fuel, while in the second mode LPG was linked directly to the engine's intake manifold, allowing it to operate on both diesel and LPG at the same time.

The parts name of the system is given in Table 3.

3.1. Injection control system (ICS)

The direct injection of LPG in gaseous form into the air intake manifold was chosen as the LPG supplementation method in this study. Overall safety devices must be included for overall safety during operation in order to minimize the risks. The LPG induction systems should have the following features in order to reach technical and safety standards:

1. The LPG gas cylinder has a capacity of 12 kg and a pressure of 10–12 bar. This cylinder was used as LPG tank to hold enough LPG for conducting the tests.
2. Using two single-stage pressure regulators to reduce the pressure of LPG from the cylinder to a pressure in the range of 2–4 bar depending on the flow rate.
3. Flow control valve to regulate the flow of LPG from the LPG storage cylinder via the pressure regulating valve and into the induction system.

Table 1 The properties of fuels under consideration (Mohsen and Al-Dawody 2022a).

Properties	Diesel	LPG
Formula	$C_{13.775}H_{24.7}$	$C_{3.624}H_{9.248}$
Density(kg/m^3)	830	2.137
Lower Calorific Value (kJ/kg)	45000.83	46000.22
Molecular weight (kg/mol)	190	52.916
A/F ratio (stoi.)	14.406	14.516
Cetane number	53.4	< 3
Octane number	–	105

Table 2 Engine information (Mohsen and Al-Dawody 2022b).

Manufacturer	Kirloskar engine (CI engine)
Design	Single cylinder,4-stroke
Bore, stroke	80 mm,110 mm
Rated power	3.7 kW
Rating speed	1500 rpm
Compression ratio	Varaible (14.5–17.5)
Injection Pressure	160 bar
Swept volume	553 cm^3
Start of injection	150C°A

4. A non-return valve is used to prevent the flame from reaching the LPG cylinder.
5. Flame trap to prevent any re-ignition of LPG and lower the temperature of LPG gas as it is delivered to the intake system.
6. Two nozzles after the flame trap to inject LPG gas into the diesel engine's inlet air manifold.
7. All of the parts of the induction system are linked by high-pressure flexible tubes with valves.

The ICS setup is seen in Fig. 3. The system receives its signal from a sensor that is situated on the engine head and is connected to a 12-volt DC source.

3.2. Flame trap

The flame trap is a metal container filled with water having entrance and outlet ports. Flames can't go inside the cylinder due to water. A flame trap is an important safety element. It is designed to prevent fire from accessing the fuel supply line. This decreases the possibility of an explosion, making the equipment easier to use. As shown in Fig. 4.

3.3. Safety valve

A non-return valve is a safety device installed in the system to prevent LPG from flowing backwards. Fig. 5 shows the safety valve.

3.4. Gas analyzer system

The capability of the diagnostic instrument to monitor CO, CO_2, O_2, HC, and NO_x emissions is illustrated in Fig. 6. Any windows machine may install software for exhaust gas analysis control. These instruments may be used without the trouble of clumsy wires via Bluetooth and the current management technology from TEXA.

3.5. Calculation of performance parameters

Data such as (engine speed fuel consumption time, and engine load applied) are collected when the engine enters thermal equilibrium. Gases including, NO_x HC, and CO, have their emission parameters monitored as well. The following equations are used to determine the rest of the results (Heywood 2018; Stone 1999).

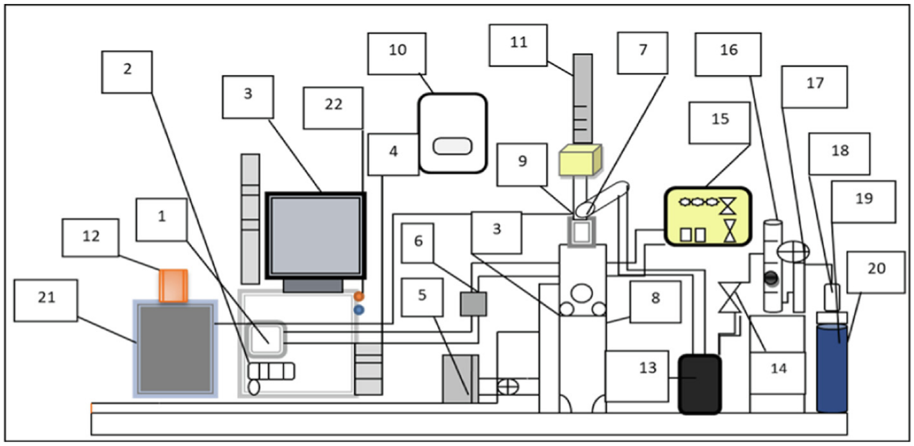

Fig. 1 Schematic test design.

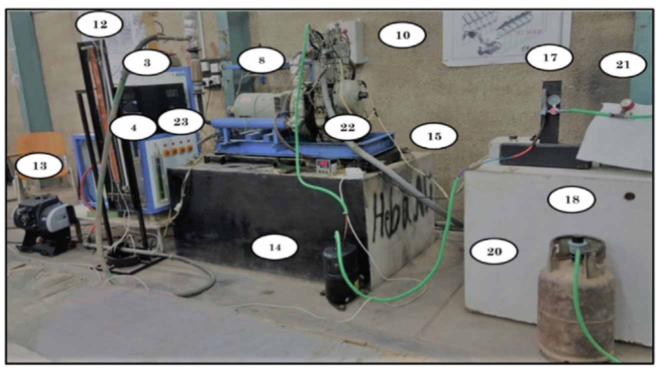

Fig. 2 The entire experimental system.

Table 3 Parts name of the system.

Parts name of the system		
1. The air surge tank	9. Cylinder head	17. Pressure regulator
2. A recorder of data	10. Voltage regulator	18. LPG pipe
3. PC control	11. Fuel tank	19. LPG cylinder
4. Manometer	12. Temperature scale	20. Pressure regulator
5. Dynamometer	13. Flame trap	21. Gas analyzer
6. Intake air	14. Safety valve	22. Load
7. Injector for fuel	15. ICS	–
8. Engine block	16. Gas flow meter	–

3.5.1. Brake power

In this study, the brake power is converted to electric power (EP), which is used to operate the heating element (resistance to heating). As a result, the following formula is used to compute brake power:

$$BP = EP = I * V * \cos\beta \quad (1)$$

Where:
I: Current electric (A), V: The voltage (V) BP = The brake power in(kW), EP = electric power in (kW).

3.5.2. Rate of fuel consumption

In order to accurately measure fuel consumption, a fuel tank, cantilever load cell, transmitter, and data recorder are needed. The fuel gauge (strain gauge) has a load scale that runs from 0 to 1000 ml. To minimize damage to the strain gauge, the tank weight, including the diesel load, should not exceed 1000 ml. The rate of fuel consumption is represented by the Eq. (2) represents difference between the beginning (m_{f1}) and finishing (m_{f2}) weights of fuel in the tank during a certain period of time (t).

$$\dot{m}_f = \frac{m_{f1} - m_{f2}}{t} \quad (2)$$

Where:
$\dot{m}_f$: The consumption rate of fuel (kg/s).
m_{f1}: The initial weight.
m_{f2}: Final weight.
t: duration of time.

3.5.3. Brake specific fuel consumption (BSFC)

It's a significant metric for determining how well the engine works. An engine's thermal efficiency is inversely related to its energy output. The Eq. (3) is used to get the BSFC values.

$$BSFC = \frac{\dot{m}_d + \dot{m}_{LPG}}{BP} * 3600 \quad (3)$$

Where,

Fig. 3 The control mechanism for LPG injection.

Fig. 4 Flame trap arrangement.

Fig. 5 Safety valve.

Fig. 6 Gas analyzer.

BSFC: Brake Specific Fuel Consumption(kg/kWh),
$\dot{m}_d$: Flow rate of diesel mass (kg/s),
$\dot{m}_{LPG}$: Flow rate of LPG mass.

3.5.4. *Brake thermal efficiency* ($\eta_{B.Th}$)

Energy in braking power divided by input fuel energy is known as Brake Thermal Efficiency (BTE). In order to determine thermal efficiency, an Eq. (4) was utilized.

$$\eta_{B.Th} = \frac{BP}{\dot{m}_d * LCV_d + \dot{m}_{LPG} * LCV_{LPG}} * 100\% \quad (4)$$

3.6. *Uncertainty analysis*

Uncertainty evaluation is done by doing any experiment three to four times and comparing the observed results to the standard deviation. The experimental measurement's uncertainty is determined using Kline and Mc. Clintock method (Holman and Gajda 2001; Kline 1953). The proportion of parameter uncertainty is displayed in Table 4 for the measurements. The following formulas are used to calculate uncertainty.

$$\Delta R = \left(\frac{\partial R}{\partial X_1}\Delta X_1 + \frac{\partial R}{\partial X_2}\Delta X_2 + \frac{\partial R}{\partial X_3}\Delta X_3 + \ldots + \frac{\partial R}{\partial X_n}\Delta X_n\right)^{0.5} \quad (5)$$

Where: ΔR is the total uncertainty of the experimental result. R-main function and relates to variables x_1, x_2.... xn., Δx_1, Δx_2 ...Δx_n- Independent variable uncertainties. Based on the study, overall uncertainty is determined within the limit of 4%.

4. Engine mathematical model

A quasi-dimensional multizone model that represents as an intermediary step between zero-dimension and multi-dimension models is utilized in this study to simulate combustion in a diesel engine.

4.1. Governing equations

4.1.1. Conservation of mass

The net flux of mass represents the amended mass rate through an open construction over the constriction restrictions and arithmetically as shown in Eq. (6) (Rajak et al. 2018):

$$\frac{dm}{dt} = \sum_i m_i \tag{6}$$

4.1.2. Conservation of species model

The analytical equation of the species conservation is shown in Eq. (7) as:

$$Y_i = \sum_i \frac{m_i}{m} \tag{7}$$

4.1.3. Conservation of energy model

For an open thermodynamic system, the standard energy equation can be defined according to (Fiveland and Assanis 2000)

$$\frac{d(mu)}{dt} = -p\frac{dv}{dt} + \frac{dQ_{ht}}{dt} + \sum_i m_i h_i \tag{8}$$

The term on left side, in Eq. (8), states the change rate in energy while the terms on the right side, from right to left, represents the entropy flux, heat transfer rate and the displacement work rate respectively.

4.2. Numerical analysis

The Russian software diesel-RK is used to simulate the combustion process. The multi-zone fuel spray combustion model given in the reference (Al-Dawody et al. 2021) is used in this investigation. The cylinders are viewed as an open thermodynamic system in this approach. Additional numerous distinguishing features can be found in (Kuleshov 2005). The fuel spray poured into the engine's combustion chamber is divided into many zones (Al-Dawody and Bhatti 2013). The velocity of an Elementary Fuel Mass (EFM) travelling from the injector to the spray tip during a small time step is described by the following equation:

$$\left(\frac{V}{V_O}\right)^{\frac{3}{2}} = 1 - \frac{l}{lm}. \tag{9}$$

Where,
V: current speed of the EFM.
V_O: initial speed of the EFM.
l: The distance from EFM to injector nozzle.
lm: The time it takes for EFM to penetrate before a spray is terminated.

The mathematical formulation of Eq. (9) can be solved as follows:

$$3l_m[1 - [1 - \frac{l}{l_m}]^{0.333}] - V_0\tau_K = 0 \tag{10}$$

Fig. 7 displays a simplified schematic of the spray.

4.3. Modeling of NO_x formation

The Zel'Dovich mechanism is used. When nitrogen dioxide combines with nitric oxide, NO_x emissions produce. Zel'Dovich's mechanism was chosen:

$$O_2 \leftrightarrow 2O \tag{11}$$

$$O + N_2 \leftrightarrow NO + N \tag{12}$$

$$O_2 + N \leftrightarrow NO + O \tag{13}$$

The rate of this reaction is affected by the atomic oxygen concentration, as shown in Eq. (13). The NO volume concentration was calculated using the following equation (Al-Dawody et al., 2022a)

$$\frac{d[NO]}{d\theta} = \frac{e^{-38020/T_z}[N_2]_e[O]_e\{1 - (\frac{[NO]}{[NO]_e})^2\} * 2.33 * 10^7 P}{RT_Z[1 + (2365/T_Z)e^{3365/T_z}[NO]/[O_2]_e]} * [\frac{1}{rps}] \tag{14}$$

5. Numerical Validation

The data produced by the experiment is compared to the results of other researchers. All parameters and operating statuses are stored in the database of the software. Fig. 8 depicts the diesel fuel spray evolution over time. There is a similar trend and strong agreement with a 5 % deviation. Fig. 9 shows the evolution of the diesel heat release rate for the current study and the study of (Al-Amir and Al-Dawody 2022). It is reasonable to state that the Diesel RK program is an excellent simulation tool for analyzing IC engine combustion characteristics.

6. Results and discussion

Studies of the dual fuel diesel engine's properties under varied conditions are done through experiments (load, LPG rate, and compression ratio). The findings attained are displayed below.

Table 4 Parameter's precision and Uncertainty.

Measurement	Accuracy	Uncertainty%
Speed	+-15 rpm	1
Time	+- 0.8 sec	0.2
Temperature	+-1.5C	0.1
CO_2	+-0.1%	0.2
CO	+- 0.1%	0.2
HC	+-1 ppm	0.2
NO_x	+-1 ppm	0.2

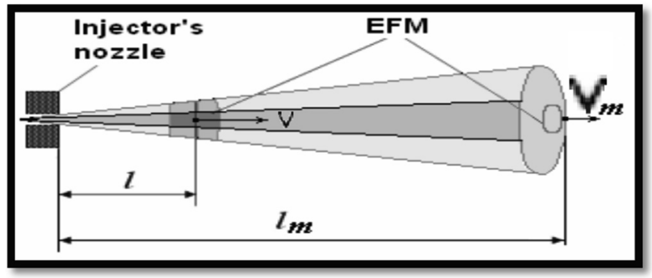

Fig. 7 Spray history diagram (Al-Dawody and Bhatti 2013).

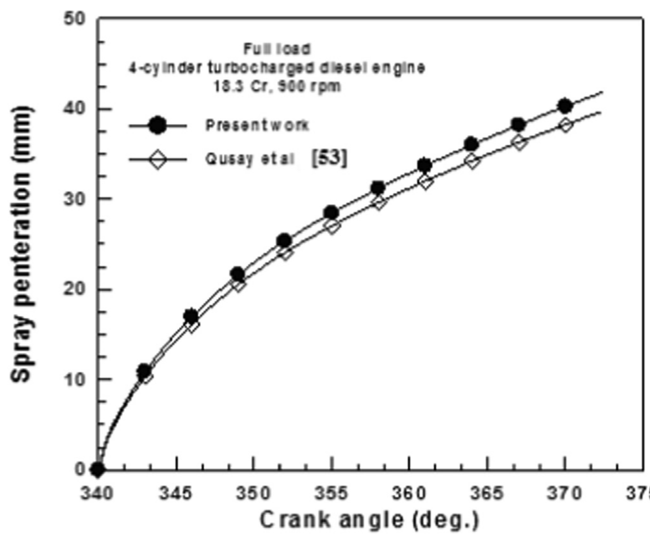

Fig. 8 Validation of full-load spray tip penetration with diesel.

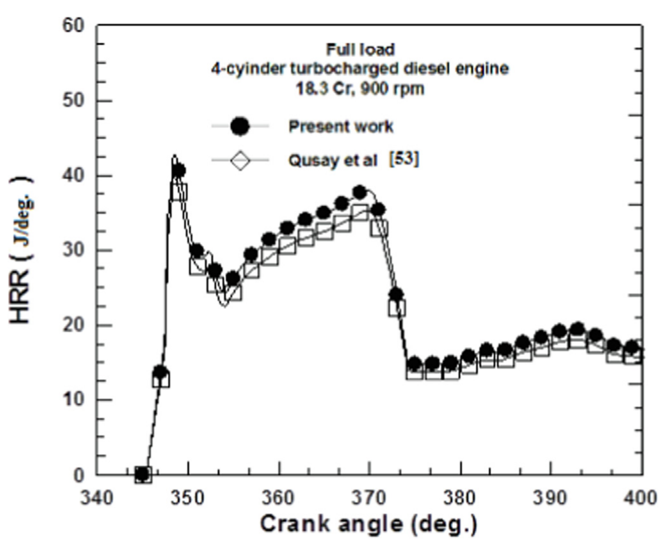

Fig. 9 Validation of the heat-release rates for diesel engines at full load.

6.1. Effects on the performance parameters

6.1.1. Brake specific fuel consumption

Fig. 10 presents the variation of Brake Specific Fuel Consumption (BSFC) with load. As the load increases, the BSFC decreased as the rate of increased power is greater than fuel consumption. It is shown in Fig. 10 that with LPG injection rates of 5, 10, 15, and 20 L/min, there are significant differences BSFC. As a result of the enhanced LPG and air dual fuel combination, the engine operates more quietly and smoothly.

Adding LPG to the mix increases engine fuel consumption, even under moderate load conditions. At 1500 rpm and full load, the BSFC is 0.3, 0.33, 0.38, and 0.42 kg/kWh at LPG injection rates of 5, 10, 15, and 20 respectively L/min same observation is noted with (Rao et al., 2010).

As shown in Fig. 11, increasing the compression ratio from 14.5 to 16.5 leads to reduction in BSFC for the mono fuel (diesel) and dual fuel operation with all LPG rates under consideration. According to this scenario the operation of engine with LPG at 15 and 20 L/min produces a reduction in BSFC by 12.5%, and 11.11% compared to diesel alone (12.21%).

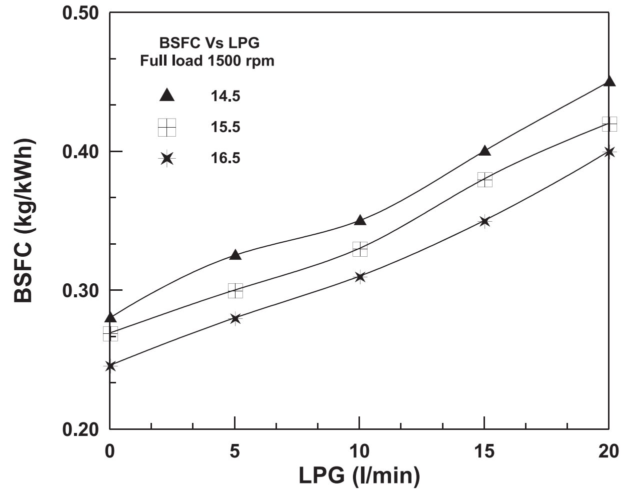

Fig. 11 Impact of LPG on BSFC.

6.1.2. *Brake thermal efficiency (BTE)*

The history of BTE with load is shown in Fig. 12. As mentioned before the dramatic increase in power with the increase in load yields to an increase in BTE for both diesel and all LPG rates. As the LPG inducted with 5 L/min, there is a decrease in BTE compared to diesel by 10.3%. Further increase in the rate of LPG causes additional drop in the value of BTE far below that of a conventional diesel engine. This is because increase in the ignition delay time by increasing gas content and decreasing pilot fuel levels. This comes fits with the results of (Sendilvelan and Sundarraj 2016).

Fig. 13 shows how BTE varies with the compression ratio. In spite of thermal loads on the engine as well as decreasing volumetric efficiency, increasing compression ratio raises BTE (Al Dawody et al. 2022b). For diesel, increasing the compression ratio from 14.5 to 16.5 leads to an increase in the BTE by 13.91 % while its increase by 16.07%, 12.90%, 14.28% and 12.5% for using 5, 10, 15, and 20 L/min of LPG consequently.

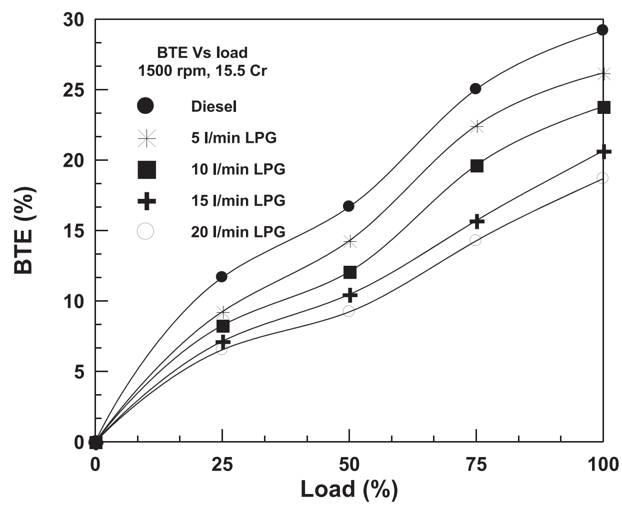

Fig. 12 Brake thermal efficiency varies with load.

6.1.3. *Volumetric efficiency*

Fig. 14 shows LPG and diesel volumetric efficiencies with variation of load. Logical reduction in the values of volumetric efficiency for all fuel under scope as increasing load means more fuel burned and larger quantity of air is required. As LPG rate increases, volumetric efficiency reduced. The loss in volumetric efficiency may be owing to increased exhaust gas temperatures or the use of LPG instead of air for induction, which is less dense than diesel. LPG reduces mixture density, as less airflow reduces volumetric efficiency. With diesel fuel at full load, the engine's volumetric efficiency is 88.827 %, but with inducting 5,10, 15, and 20 L/min of LPG, it dropped to 85.062%, 82.562%, 81.8362%, and 81.0652%, respectively.

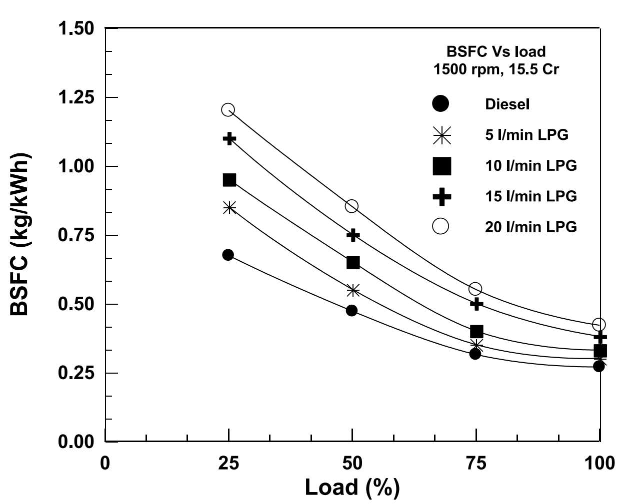

Fig. 10 Variation of BSFC with load.

Fig. 15 presents the variance of volumetric efficiency with compression ratio. When the compression ratio is raised, volumetric efficiency is reduced. This is due to the high temperatures in the combustion chamber and the increased pressure and temperature of the residual gas in the clearance volume. The volumetric efficiency decreased when compression ratio increased from 14.5 to 16.5. It decreased for diesel by 0.355%, while for LPG (5, 10, 15 and 20) L/min, the drop was approximately 1.74%, 2.78%, 1.99%, and 1.46%, respectively.

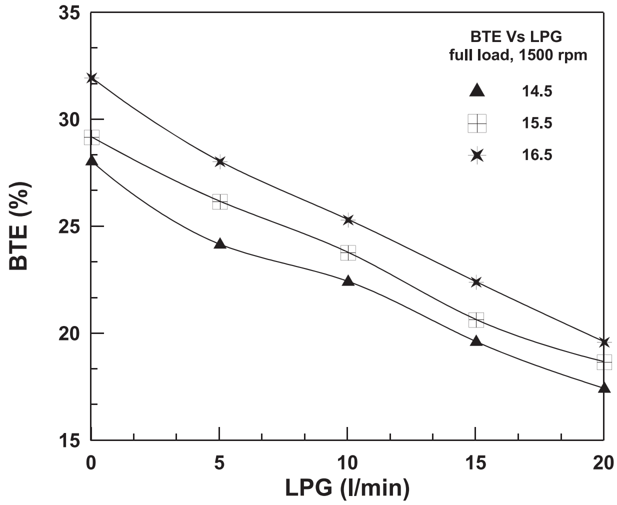

Fig. 13 Impact of LPG on BTE.

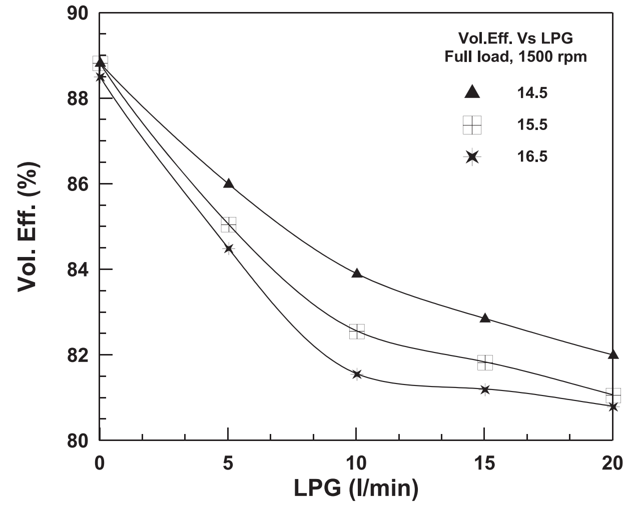

Fig. 15 Impact of LPG on volumetric efficiency.

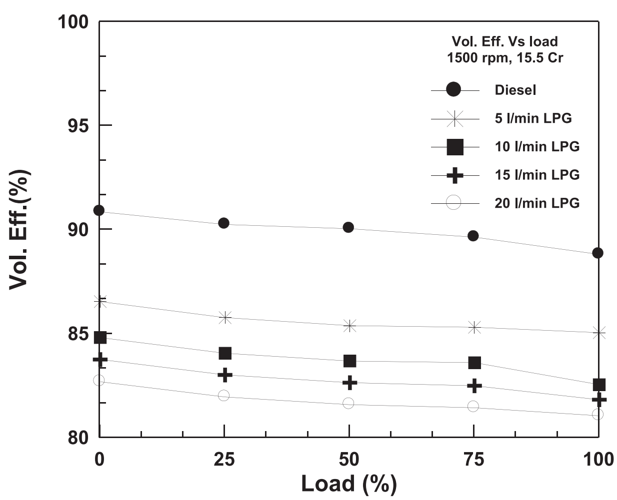

Fig. 14 Volumetric efficiency varies with load.

6.2. The effects on emission parameters

6.2.1. Carbon monoxide (CO)

Carbon monoxide is a toxic gas that contributes to the development of conditions that are dangerous to the environment. Fig. 16 illustrates history of CO emissions with load. As the load increases, the engine emits more CO due to insufficient time for mixture formation at high loads as well as increased fuel injected per stroke, which in turn leads to increased fuel–air ratio and makes the combustion poor (Süleyman et al., 2021b). The presence of LPG releases less CO compared to the use of diesel alone. At full load, emissions are at their highest, so this extreme case is taken into account so that the best rate choice is significantly requested. The LPG engine generates CO less than a diesel engine by 20 %.

Different LPG induction rates and compression ratios result in different CO levels in exhaust gases, as shown in Fig. 17. When the compression ratio is increased from (14.5 to 16.5), both diesel and LPG's CO emissions dropped because of the shorter combustion time which suppress the formation of CO. As a result, for LPG flow rates of 5, 10, 15, and 20 L/min CO is reduced by 16.6%, 14.7%, 20.3%, and 18.8% respectively, compared to the case of diesel 15.9%.

6.2.2. Hydrocarbon (HC)

Some of the fuel supplied into the engine is released as hydrocarbon (HC) emissions as a result of incomplete combustion. All types of factors, including fuel absorption and emission, flame quenching and fuel evaporation, and fuel deposition in engine deposits, all contribute to the emission of HC (Al-Kaabi et al., 2020). Lower HC emissions were achieved by using LPG to execute a more efficient combustion reaction with a diesel pilot fuel. As a result of this activity, less unburned fuel has been generated. Fig. 18 depicts the change of HC when the load is varied from (0 to 100) %. LPG was used to perform a more efficient combustion reaction with die-

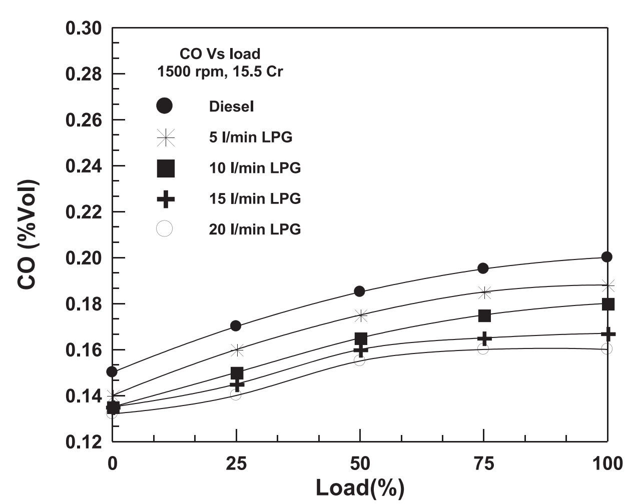

Fig. 16 CO emissions varies with load.

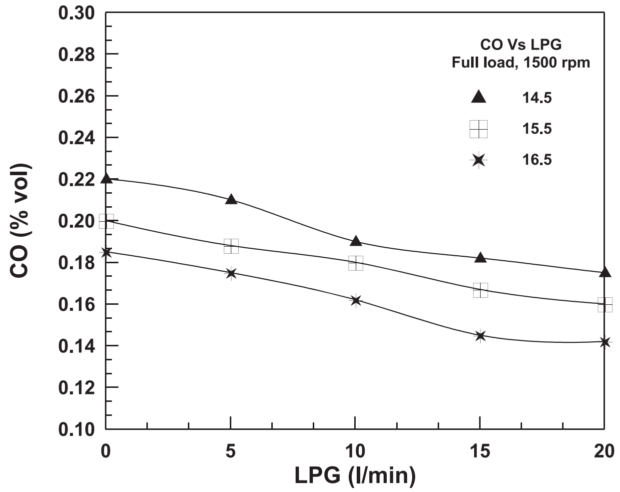

Fig. 17 The Variation of CO with load at different compression ratio.

sel pilot fuel, resulting in lower HC emissions from a variety of LPG mixtures. This action has also contributed to a reduction in unburned fuel. The greatest reduction in HC emissions occurs when the engine runs at 75% load and the LPG blending flow rate is 20 L/min with a compression ratio of 15.5. The decrease in HC emissions at full load is 6.8%, 11.3%, 17.3%, and 21.76% for LPG of (5, 10, 15, and 20) L/min, respectively. The decrease in HC is related to the increased combustion velocity of LPG and less carbon in LPG composition which improves combustion and reduces HC. Other research in the literature (Qi et al., 2007) corroborated these results.

5 L/min, 10 L/min, 15 L/min, and 20 L/min LPG flow rates, reduced HC emissions by (6.8%, 11.3%, 17.3%, and 21.76%) respectively. Same trends are noticed with the results of (Qi et al., 2007).

Fig. 19 shows the differences in HC emission as a function of the LPG induction rate for a variety of compression ratios. If the compression ratio is increased, then the air temperature at the end of the compression stroke will also be increased. This will result in an increase in the temperature of the combustion process. Diesel's rate of reduction in HC emissions is 6.77%, while adding LPG at rates of 5, 10, 15, and 20 L/min results in reductions of 4.54%, 4.76%, 8%, and 6.38%, respectively.

6.2.3. Nitrogen oxide (NO_x) emission

NO_x is depending on a variety of variables, such as the cylinder temperature, the proportion of oxygen present, and the amount of time necessary for the reaction to occur during combustion. Higher amount of oxygen and higher temperature in the combustion chamber make the amount of nitrogen oxides that are released goes up. NO_x is a product of internal combustion engines; it is formed from nitrogen dioxide (NO_2) and nitrogen monoxide (NO) in the exhaust (Al-Dawody and Bhatti 2013). The NO_x emissions from a dual-fuel engine that uses LPG are lower than those from a diesel engine only. The most nitrogen oxides come out of the exhaust when the load is at its highest point. Fig. 20 shows NO_x concentrations vs. load. Pure diesel emits less NO_x compared to all LPG rates at full load diesel emits NO_x 1220 ppm compared to LPG concentrations of about 1150, 1100, 1070, and 1020 ppm for 5, 10, 15, and 20 L/min of LPG, respectively.

As seen in Fig. 21, as the compression ratio increased, NO_x emissions increased. NO_x formed more rapidly when the combustion pressure and temperature are increased due to increase in the compression ratio. At 16.5 NO_x emission values for 5, 10, 15, and 20 L/min of LPG operation are 1200 ppm, 1150 ppm, 1100 ppm, and 1050 ppm, respectively, compared to 1300 ppm for diesel.

6.3. Combustion characteristics

Many elements, such as fuel quality, cetane number, fuel optimization, fuel evaporation rate, combustion chamber design, injection timing, compression ratio, and pressure, have an impact on combustion in diesel engines (Süleyman 2020a). The simulation results concerning pressure history, heat release profile, peak pressure and temperature are discussed in the next lines below:

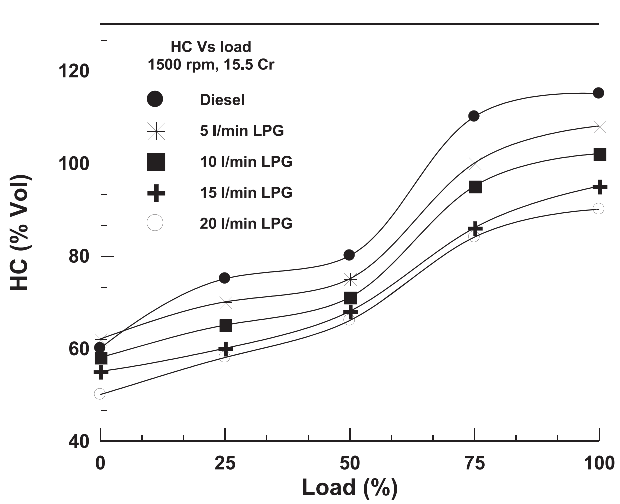

Fig. 18 The Variation of HC with load.

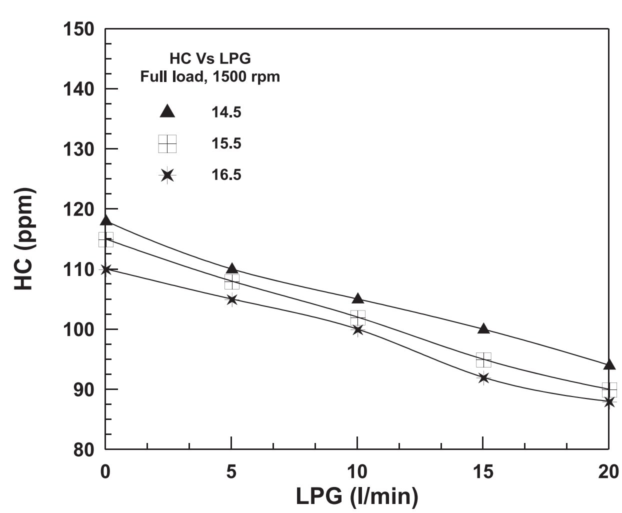

Fig. 19 The Variation of HC with load at different compression ratio.

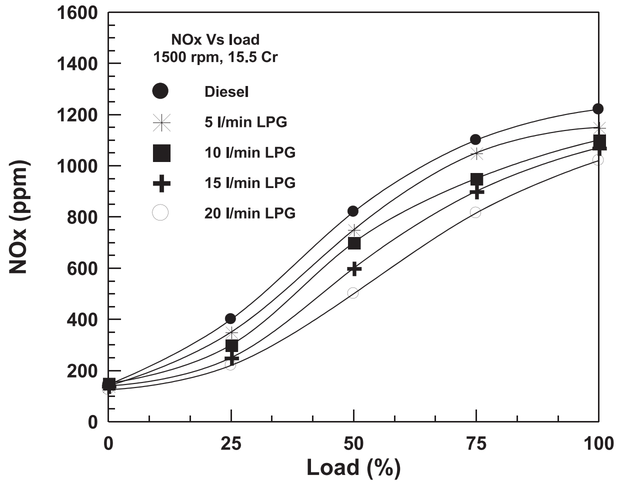

Fig. 20 NO_x variance with load.

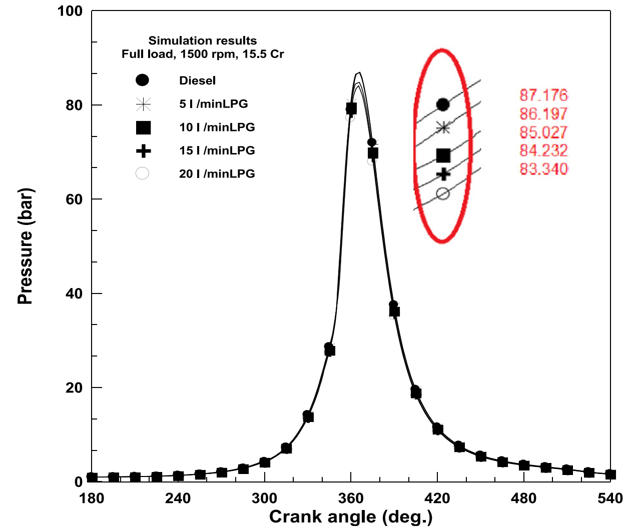

Fig. 22 Cylinder pressure vs. crank angle.

6.3.1. Cylinder Pressure

The relationship between cylinder pressure and crank angle is shown in Fig. 22 for pre diesel and various LPG flow rates, starting with 5 L/min and going all the way to 20 L/min. The diagram clearly shows that an increase in LPG use causes pressure to decrease. Maximum operating pressure for diesel fuel is 87.176 bar, whereas maximum pressure for 5, 10, 15, and 20 L/min of LPG is 86.197 bar, 85.027 bar, 84.232 bar, and 83.340 bar respectively. The same results are found in (Al-Amir and Al-Dawody 2022).

6.3.2. Rate of heat release

Fig. 23 illustrates the relationship between rate of heat release and crank angle. When LPG is inducted the time between injection and combustion is reduced, allowing combustion to begin sooner and producing less heat. Diesel's peak energy production is 32.53 (J/deg.) at 365 degrees BTDC, although at 365 degrees BTDC it is simply 30.28, 29.04, 29.62, and 30.24(J/deg.) BTDC is used for LPG concentrations of (5, 10, 15, and 20) L/min. Since the combustion is decreased as a result of LPG induction, slight decrease in the rate of heat release is noticed.

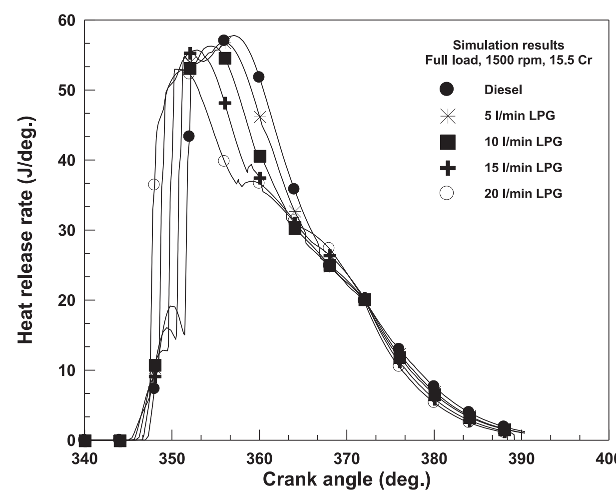

Fig. 23 The heat release rate vs. crank angle.

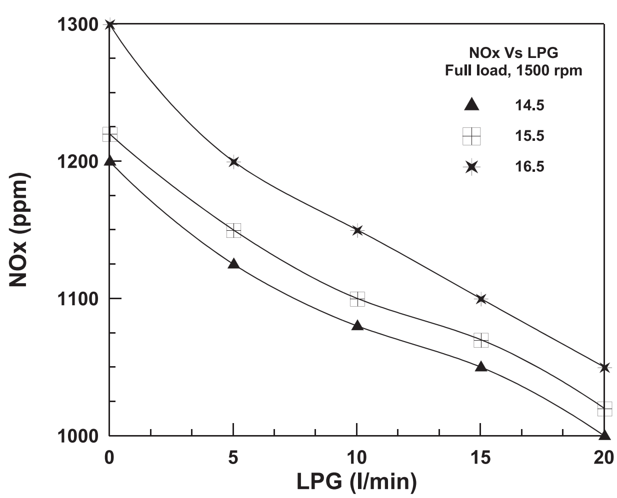

Fig. 21 The Variation of NO_x with load at different compression ratio.

6.3.3. Peak pressure

Fig. 24 illustrates the variation of peak pressure for diesel and LPG with varying compression ratios. According to the findings of this investigation, increasing the compression ratio resulted in a significant increase in peak pressure for various fuels. Diesel generated the greatest pressure 94.357 bar at 16.5 compression ratio followed by 93.564 bar for 5 L/min LPG, while the values of peak pressure for other rates of LPG 10, 15, and 20 L/min are 92.237 bar, 91.386 bar, and 90.4597 bar, respectively.

6.3.4. Peak temperature

Fig. 25 illustrates the effect of variable compression ratio on the peak combustion temperature. As the compression ratio increased, the peak temperature is increased. The highest temperatures are reached with pure diesel at a compression ratio

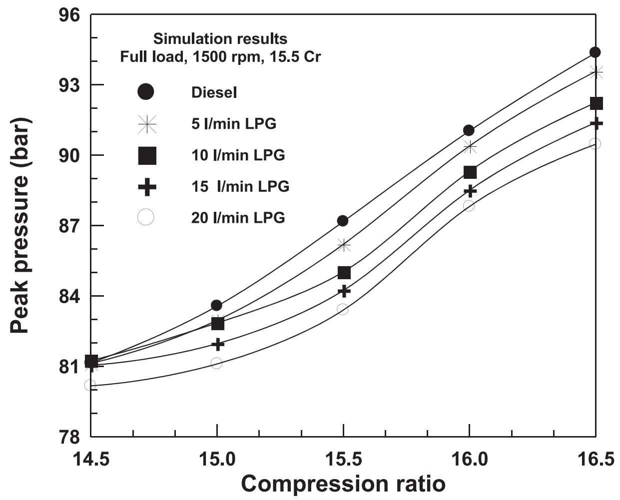

Fig. 24 The effect of compression ratio on the peak pressure.

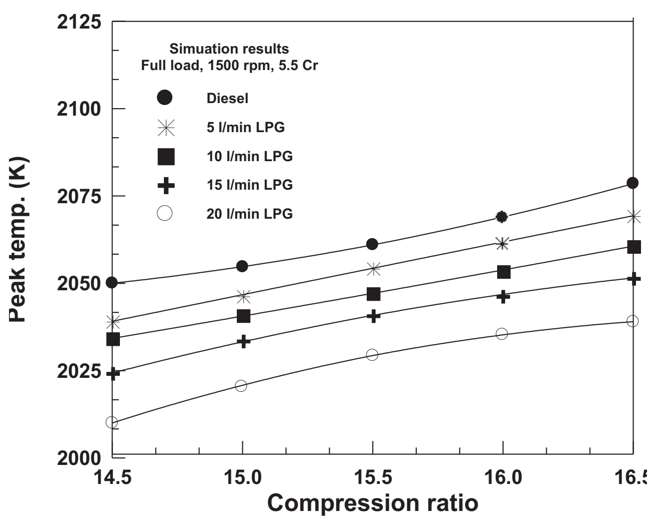

Fig. 25 The effect of compression ratio on peak temperature.

Table 5 Experimental with Theoretical exhaust temperature.

Fuel	T_{exh} (exp.) %	T_{exh} (sim.) %	Deviation (%)
DF	280	273.48	2.32
5 L/min LPG	275	271.46	1.28
10 L/min LPG	265	270.8	2.14
15 L/min LPG	265	268.86	1.43
20 L/min LPG	260	267.06	2.64

of 16.5, which is 2078.5 K whereas its 2069.3 K for 5 L/min of LPG which is the highest temperature compared to other rates of LPG.

7. The comparison of the results between simulations and experiments

At maximum load and a standard compression ratio of 15.5, the simulation findings are compared with the experimental results. Fig. 26 compares volumetric efficiency that investigated experimentally and numerically. The Diesel-RK program showed most impressive findings, closely followed by experimental research. The deviation for diesel is (4.06%), whereas it is 8.07%, 10.7%, 11.5%, and 12.3% for LPG with rate of 5 L/min, 10 L/min, 15 L/min, and 20 L/min, respectively.

Table 5 compares the experimental and theoretical exhaust temperature it can be seen that simulation results matches well with the experimental findings with acceptable deviation. The maximum deviation recorded is 2.64% in case of inducting LPG with 20 L/min while the minimum one recoded for the operation with 5 L/min (1.28%).

8. Conclusion

The induction of LPG reduces the BTE, while increases BSFC. The volumetric efficiency decreased for all rates of LPG used. The exhaust temperature decreased as rate of inducted LPG is

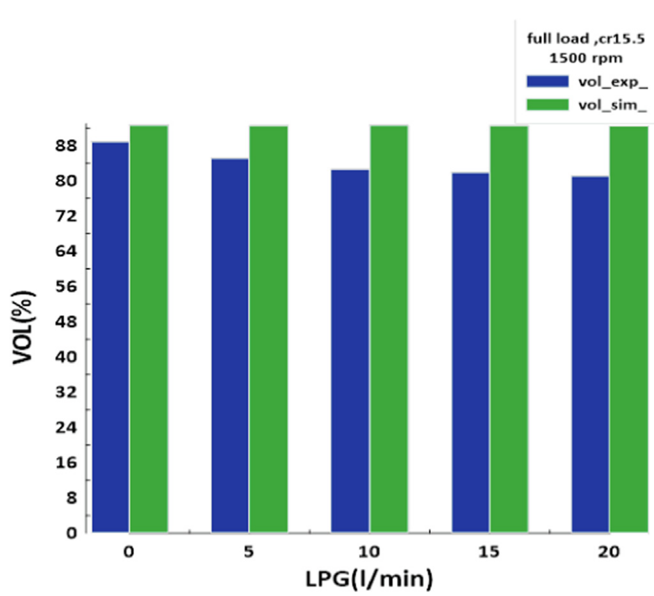

Fig. 26 The volumetric efficiency with LPG rate.

increased. Significant reduction in CO, HC and NO_x emissions with the use of LPG. Numerically inducting LPG lowers peak pressure and temperature by 4% and 1.5% consequently for 20 L/min with a compression ratio of 15.5. as well as slight reduction in the heat release rate is obtained. As the compression ratio increased from 14.5 to 16.5, the BTE increased by 12.5% and the BSFC is decreased by 11.11% at an induction rate of 20 L/min. The pollutants emissions are also impacted with variable compression ratio where CO and HC reduced by 23.2% and 20% respectively at an induction rate of 20 L/min. Inducting LPG at a rate of 15–20 L/min represents the best compromise rate.

CRediT authorship contribution statement

Maysaa J. Mohsen: Formal analysis, Software, Writing – original draft. **Mohamed F. Al-Dawody:** Investigation, Writing - original draft. **Wasim Jamshed:** Methodology. **Amjad Iqbal:** Writing – review & editing. **Sayed M El Din:** Data curation, Visualization, **Assmaa Abd-Elmonem:** Validation, Project administration **Nesreen Sirelkhtam Elmki Abdalla:** Supervision **Hamad Hussain Shah:** Formal analysis

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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