LPG-Diesel Dual Fuel Emission Characteristics: A Review

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ABSTRACT

The global shift away from fossil fuels for energy, driven by concerns about emissions and energy security, has sparked significant interest in alternative fuels. One promising approach involves combining alternative fuels, like Liquefied Petroleum Gas (LPG), with traditional diesel engines. This strategy, known as the dual-fuel concept, aims to harness the strengths of each fuel type while reducing emissions and improving engine performance. This review focuses primarily on LPG as a dual fuel for diesel engines. LPG, a gaseous fuel primarily composed of propane and butane, offers substantial environmental benefits, including a 15% reduction in CO2 emissions, a 30% reduction in CO emissions, and a 50% reduction in NOx emissions compared to diesel. However, using pure LPG in diesel engines faces a challenge related to its ignition behavior. This challenge can be overcome by blending LPG with substances like Hydrotreated Vegetable Oil (HVO) or diesel fuel, which act as ignition enhancers. The main goal of this review is to provide a comprehensive overview of the potential advantages and applicability of the dual-fuel system combining diesel and LPG. It will explore various experimental setups, designs, and injection techniques, presenting diverse findings related to both engine performance and emissions. Additionally, the review will discuss additives that can further improve the combustion process. Overall, the research highlights the promising role of LPG as a dual fuel in reducing emissions and enhancing the efficiency of diesel engines, contributing to a more sustainable energy future.

Introduction

The diesel engine stands as one of the most remarkable inventions in the history of the automotive industry, power generation, locomotives, and various industrial applications. Its widespread utilization across diverse sectors can be attributed to its exceptional combustion efficiency, resilience, and dependability as compression ignition engines (CIEs) when compared to their counterpart, spark ignition engines (SIEs) [1]. However, CIEs are a significant source of pollution due to the substantial release of harmful emissions from the exhaust, which encompass Particulate matter (PM), hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) are some of the emissions that have a significant impact on the generation of pollutants like ozone (O3), secondary organic aerosols (SOAs), and photochemical smog ultimately leading to the creation of haze and posing serious threats to human health and ecosystems, particularly in urban areas [2, 3].

The ambient air pollution resulting from this engine type is associated with grave acute and chronic health issues, including premature mortality, respiratory disorders, heart diseases, lung cancer, cardiovascular problems, and various respiratory illnesses [4]. Notably, over 40 studies have assessed the risk of developing lung cancer due to occupational exposure to diesel exhaust. Furthermore, on June 12, 2012, the World Health Organization (WHO) classified the exhaust emissions of CIEs diesel engines as carcinogenic [5]. Consequently, according to the WHO's May 2018 report, approximately 4.2 million annual deaths are primarily attributed to exposure to polluted ambient air [6].

In addition, the effect of ultrafine (particles with a diameter less than 0.1 μm) on human well-being remains a topic with unclear implications, as evidenced by the lack of established air quality standards pertaining to this specific pollutant category. Ultrafine particles may pose a greater threat to individuals than PM2.5 and PM10 due to their smaller size enabling them to delve further into the respiratory system and potentially migrate to various organs. [7]. Diesel engines also present additional challenges, such as elevated noise levels and substantial consumption of oil-derived fuels. Considering these issues, the adoption of new dual-fuel systems emerges as a promising alternative to reduce reliance on traditional fuels [8]. Combustion noise emerges as a significant factor, being the primary source of noise in CIEs vehicles. This noise arises from the combination of mechanical forces and pressure within the combustion chamber during the engine's operation cycles. Consequently, the combustion process results in a sudden pressure surge, leading to engine block vibrations and subsequent noise emissions [9].

In the pursuit of reducing consumption dependence on fossil fuels, enhancing combustibility, and minimizing emissions, there has been a notable surge in demand for and research on alternative fuels [10]. Currently, there is global interest and extensive research into blending alternative fuels derived from various sources with diesel fuel. The goal is to ascertain the advantages of each fuel type and their effects on emissions, engine combustion characteristics, and performance [11].

Dual fuel is a combustion strategy designed to enhance combustion efficiency and reduce emissions by utilizing two distinct fuels, primarily Diesel fuel in conjunction with either natural gas or liquified petroleum gas (LPG). Dual-fuel engines offer various advantages when compared to traditional CIEs or SIEs engines [12, 13]. LPG is widely available across the globe, sourced from fossil fuel reserves, and is produced during the petroleum refining process, which involves crude oil. It can also be extracted from petroleum or natural gas streams. Nonetheless, a significant limitation associated with the utilization of LPG in diesel-engines is its less-than-ideal autoignition characteristics. To tackle this problem, a viable approach is to mix LPG with either Hydrotreated Vegetable Oil (HVO) or diesel fuel, which can act as means to enhance ignition. [14]. LPG offers several benefits for economical and fuel-efficient transportation, including abundant resources, a relatively favorable cost, and a clean fuel profile with lower greenhouse gas emissions. LPG, consisting mainly of propane and butane, holds promise as a cleaner fuel option for internal combustion engines (ICEs) since it has the potential to decrease carbon dioxide and carbonized emissions in exhaust emissions. This is due to its lower carbon content when compared to traditional gasoline and diesel fuels [15]. Under typical room temperatures, LPG retains its liquid state under roughly 8 bars of pressure, making it an economical choice for storage and transportation, as mentioned earlier, which sets it apart from other gas-based fuels [16].

This paper provides an extensive literature review highlighting the potential advantages and applications of dual-fuel diesel-LPG systems. This review will encompass multiple diesel engines and various operational conditions, along with their corresponding outcomes when used as dual fuel with liquified petroleum gas. Furthermore, it will present different designs and injection techniques, examining their impact on performance and emissions. To facilitate comprehension, this literature review will be structured into distinct sections. Initially, it will introduce LPG as an alternative fuel, followed by an explanation of LPG-Diesel dual-fuel operation. Subsequently, it will delve into emission characteristics, fuel types, and additives aimed at enhancing the emissions of LPG fuel. Finally, the review will provide in-depth insights into engine performance and combustion characteristics. This structured approach will aid in a clearer and more focused understanding of the dual-fuel diesel-LPG concept.

Liquified Petroleum Gas LPG as Alternative Fuel

Autogas, also known as LPG, is a byproduct of natural gas, which is a mixture of hydrocarbon gases, primarily propane (C_3H_8) and butane (C_4H_{10}), although it may also contain some unsaturated components like propylene (C_3H_6) and butylene (C_4H_8), as well as acetylene. Furthermore, LPG can consist predominantly of propane but may also contain almost more than 50% butane (Gas components). In the context of fossil-derived gases from natural gas, they are classified as LPG, LNG (Liquefied Natural Gas) and CNG (Compressed Natural Gas) are utilized as fuels in motor vehicles. In this discussion, our focus will be on LPG as a dual fuel option for diesel engines. LPG is a transparent gas, and its utilization leads to a reduction of approximately 2.5% in CO_2 exhaust emissions compared to diesel operations [17]. Moreover, LPG usage results in CO emissions that are 30% lower than those produced by gasoline and a 50% reduction in NOx emissions [18].

Physicochemical Properties of LPG

The considerable benefit of Liquefied Petroleum Gas (LPG) having a high ignition temperature is that it allows for the maintenance of the compression ratio in traditional Diesel engines. In a 2007 study [19], an experiment was conducted on a single-cylinder direct ignition (DI) engine. The diesel engine was altered to run on a mixture of LPG and Diesel at different ratios (0%, 10%, 20%, 30%, 40%). Additionally, when the LPG concentration in the mixture rises, both the mass-based lower heating value and the heat needed for evaporation of the combined fuel increase, while the volume-based lower heating value decreases.

Equation 1: The following formula is utilized to articulate the proportion of LPG by mass in the mixed fuel.

$$z = \frac{\dot{m}_{LPG}}{\dot{m}_{Diesel} + \dot{m}_{LPG}} \times 100\%$$

The different values of z denote the composition of blended fuels, with z = 0% indicating exclusive use of diesel, and z = 10%, 20%, 30%, and 40% signifying varying proportions of LPG within the fuel mixture.

As previously stated in the introduction, it was noted that under normal ambient conditions, LPG exists in liquid form at approximately 8 bars of pressure. Furthermore, at the upper range of typical ambient temperatures. The pressure level remains moderate, with the vapor pressure of propane at 55 °C being approximately 20 bar. This condition allows for cost-effective operations.

Table 1: The different properties and compositions of LPG, note that some numbers have been rounded. [20]

Gas Properties	Isobutane	Butane	Propane
Chemical Formula	C_4H_{10}	C_4H_{10}	C_3H_8
Vol.%	< 1	80	100 - 20
Energy Content: MJ/m^3	110.4	111.4	95.8
Energy Content: MJ/kg	45.59	47.39	49.58
Energy Content: MJ/L	25	27.5	25.3
Boiling Temp: C°	-11.75	-0.4	-42
Pressure @ 21℃: kPa	310.9	215.1	858.7
Flame Temp: C°	1975	1970	1967
Gas Volume: m^3/kg	0.402	0.405	0.54
Relative Density: H_2O	0.6	0.58	0.51
Relative Density: air	2.07	2	1.53
Density @ 15℃: kg/m^3	2.533	2.544	1.899

Storage and transportation of LPG offer distinct advantages over other gaseous fuels. Due to its greater density compared to air, LPG tends to collect in lower areas in the event of a leak, forming a layer near the ground. Unlike lighter gases such as hydrogen or natural gas, LPG does not easily disperse through small vents. Consequently, this trait enhances the likelihood of flammable mixtures developing close to the ground when there are fuel system leaks. Therefore, it is crucial to exercise caution to prevent leaks and to develop robust explosion protection techniques and methods to mitigate the potential hazards arising from such leaks [16]. Table 1 illustrates variations in the composition of LPG mixtures from one country to another. For instance, the propane-to-butane ratio in LPG mixtures differs as follows: Austria ranges from 100:0 to 80:20, Belgium utilizes a 60:40 mix, Italy's ratio varies from 90:10 to 20:80 depending on the season, the United Kingdom employs a 100:0 ratio with separate availability of butane, the USA utilizes a 100:0 LPG mixture, and Turkey's ratio fluctuates between 50:50 and 30:70 depending on the season [20,21]. Notably, some countries operate for a propane-rich LPG gas mixture during winter to ensure effective vaporization.

Propane boasts a significant advantage with its lower boiling point of -42°C compared to butane's -0.4°C. Consequently, in colder weather conditions, propane readily transitions into a gas state and vaporizes, resulting in a higher proportion of propane relative to butane in LPG gas mixtures during winter season, as observed in Italy and Turkey [22].

LPG Used in Diesel Engine

Many internal combustion engine (ICE) cars are designed to run on specific fuel systems, such as diesel or gasoline. Consequently, there are no diesel equipment systems that are ideally suited for both fuel systems. When using liquefied petroleum gas (LPG), various challenges arise, including power losses and the need to adjust the composition of exhaust gases. Therefore, it becomes evident that ICEs running on LPG can only operate optimally after carefully adjusting all engine and diesel equipment systems [23].

In 1928, Liquefied Petroleum Gas (LPG) found its first application as a motor fuel in a truck. Fast forward to 1965, Chevrolet introduced four new engines that ran on LPG for commercial vehicles. In the 1970s, Toyota developed a range of engines specifically designed for LPG use [24]. LPG boasts an octane rating (measured by MON/RON) that falls within the 90 to 110 range and an energy content (QHHV, LPG - higher heating value) that varies from 25.5 MJ/L for pure propane to 28.7 MJ/L for pure butane, depending on the specific fuel composition. However, LPG's less-than-ideal autoignition characteristics pose challenges for its use as the primary fuel in compression ignition engines. As a result, it is preferable to mix LPG with a more reactive fuel, such as diesel or hydrotreated vegetable oil (HVO), for combustion. Furthermore, when LPG is blended with HVO, its higher cetane number can further enhance the combustion process [25].

Maintenance needs for LPG vehicles closely resemble those of diesel vehicles, and the time required for refueling is about the same. However, a notable challenge arises when it comes to fitting LPG pressure containers in cars, which typically end up being bulkier and heavier compared to diesel tanks. This happens for two primary reasons: firstly, LPG possesses a lower energy density than diesel, necessitating a larger tank to cover the same driving distances, and secondly, LPG pressure containers are filled only up to 80% of their total capacity [26]. In order to adapt a diesel engine for dual-mode functionality, in which LPG serves as the main fuel source while diesel functions as the ignition source, a dedicated configuration is employed. This configuration consists of a pressure regulator, flame trap, and a bypass valve designed to introduce LPG into the engine [27].

Various techniques for fuel injection and the mixing of dual-fuel diesel-LPG systems. Below are the summarized findings from different studies:

- In order to address the extended ignition delay associated with LPG, experiments were carried out using LPG-HVO blends in a modified Diesel Engine (DE). Various injection strategies, such as no injections, one injection, or two pilot injections, were employed at different temperatures and pressures. Notably, utilizing two pilot injections led to a significant reduction in ignition delay compared to using just one. An enhanced reduction in autoignition was observed when injection pressure was set at 1250 bar with an upgraded common-rail system [14].

- In the context of homogeneous charge compression ignition (HCCI) combustion, LPG was employed as the primary fuel. It was introduced along with the intake air and underwent compression, similar to a conventional diesel engine (refer to Figure 1) [28, 29]. Due to its high self-ignition temperature, the mixture did not spontaneously ignite. Instead, a small amount of diesel fuel, known as the pilot injection, was introduced near the end of the compression stroke to initiate the combustion process. To elevate the intake charge temperature, an electric heater preheated the intake air. Combustion was initiated by the diesel pilot injection after the premixed and preheated intake air and LPG were introduced into the combustion chamber [30, 31].

- A research study investigated the spray patterns and combustion characteristics of a combination of LPG fuel and biodiesel at different blending ratios under compressed ignition conditions in a constant volume chamber. The results showed that improving the cetane value had a positive effect on ignition. Specifically, a blend consisting of 20% biodiesel exhibited superior combustion properties compared to pure LPG and other mixed fuel scenarios. Higher levels of biodiesel blending resulted in decreased emissions of CO and HC but increased emissions of CO2 and NOx [32].

- The use of two direct injectors per cylinder, with one dedicated to diesel ignition and the other supplying energy from LPG fuel, proved to be an effective approach. The shift from running solely on diesel to a combination of diesel and LPG yielded favorable outcomes, such as improved brake mean effective pressure (BMEP) and enhanced fuel conversion efficiency. This method shows promise for developing highly efficient dual-fuel LPG and diesel engines, which may require modifications to the diesel engine by integrating a second direct injector for each cylinder along with the corresponding fuel systems [33].

A gas reduction system equipped with a water heat exchanger is essential for the modified DE (Design Element). Its primary purpose is to transform liquefied LPG into a gaseous state while ensuring a consistent temperature. The water/gas heat exchanger can be classified based on both control method and flow rate.

1The various LPG fuel delivery systems can be categorized based on their control principles. To begin with, the most basic approach to fuel delivery involves a mechanically constant gas flow rate throttle, which lacks active regulation. Second, the gas flow rate throttle can be regulated through the utilization of vacuum created within the flammable mixture delivery system of an internal combustion (IC) engine, dependent on the pressure within the intake manifold. Thirdly, electronic throttle control provides an alternative means of achieving this regulation. Lastly, the gas injection system can be controlled and distributed to the cylinders through electronic control unit (ECU) supervision.

There are three potential approaches for utilizing LPG as a fuel source for heavy duty vehicles:

1. Substituting a diesel engine with a gas engine.
2. Installing an LPG delivery system while retaining the vehicle's primary fuel delivery system.
3. Completing extensive modifications on a diesel engine to make it fully compatible with LPG as the sole fuel source.

The second method involves delivering a mixture of LPG and air through the intake manifold in a diesel engine. Simultaneously, a reduced quantity of diesel is injected into the cylinders to initiate ignition [26]. This approach was chosen to enhance fuel efficiency and decrease exhaust emissions. However, while the addition of the LPG delivery system is relatively straightforward, it does not provide all the advantages associated with dedicated gas engines.

The third approach is widely regarded as the preferred option.as it involves comprehensive modifications to the original diesel engine (DE) rather than replacing it with a specialized gas engine designed for LPG. This approach eliminates the need for additional design complexities, such as adapting a new engine to the gearbox and clutch. When heavy-duty DEs undergo these modifications, it is expected to extend the period between technical maintenance services. Nonetheless, due to the substantial weight of these vehicles, energy consumption is likely to increase significantly.

LPG Diesel Dual Fuel Operation

Reciprocating ICE including diesel engines operate on a common principle. Initially, a combustion mixture gets compressed into a combustion chamber, followed by ignition. The resulting high-temperature and pressure gases then drive the piston downward, causing the crankshaft to rotate. These engines employ two ignition methods: first, spark ignition SI which include injecting the fuel through the intake manifold along with air to combust once the spark starts in the combustion cycle, second, compression ignition CI which replaces the spark place in the engine by an injector that inject diesel after the compression cycle to ignite the fuel. Thus, DE is a part of CI engines which utilize the compression ignition method, where the injected fuel is at high pressure just before combustion commences, leading to ignition.

Liquefied petroleum gas could be used in DE either as a liquid or gas. Firstly, LPG as liquid is blended with diesel at pressures of 0.5 MPa or higher. This mixture is subsequently pressurized by a pump with higher peak pressure range, which moves the dual fuel blend to the injector for each cylinder. Thus, liquefied LPG could be used in the DE through one common injector as a mixture, else, each fuel could be delivered separately using two injectors per cylinder [34, 35, 36].

LPG in Gaseous Form

In its gaseous state, LPG is introduced into the intake manifold of air, forming a blend of air and LPG before entering the cylinder. This mixture is then compressed, similar to a normal DE process. However, due to the air-LPG blend high self-ignition temperature, it fails to auto-ignite. To initiate combustion, a little quantity of diesel fuel, referred to as pilot because it initiates the combustion, will be injected into a combustion chamber just before ignition. Numerous research endeavors in the field of Diesel-LPG fuels that works on DE undertaken by various researchers [19].

G.A. Rao [37] conducted an experiment to assess the engine characteristics and focusing on the efficiency while operating with Diesel-LPG. For the experiment, a 4-stroke DE was changed to adapt the operation of dual-fuel LPG-Diesel. Therefore, fuel injector was adjusted to inject only diesel as main pilot fuel, while the intake manifold was modified as the old designs to have carburetor which used to help in the mixture process. Thus, dynamometer of the eddy current type has been used for this modified DE engine, and the full engine has been linked to computer system to share the combustion parameters data and analyze it.

Moreover, the experiments involved maintaining speed of 1500 rpm that is fixed for the whole experiment while injecting different amounts of fuel (LPG) thought the inlet manifold, specifically at levels of 10%, 20%, 30%, 40%, and 50%. Comparing the effective efficiency between different LPG loads and a pure diesel engine, it was evident that the dual-fuel approach proved to be more cost-effective and convenient for preserving liquid fuels. Using dual fuel, it was observed that minor adjustments to the diesel baseline engines allowed them to operate effectively. Generally, when it comes to performance metrics like mechanical efficiency and brake thermal efficiency BTE, single-fuel operation outperforms dual-fuel mode till it reach a load near 35%. However, at greater values of engine loads, the Diesel-LPG operation demonstrates superiority over single-fuel running, as illustrated in Figures 1 and 2.

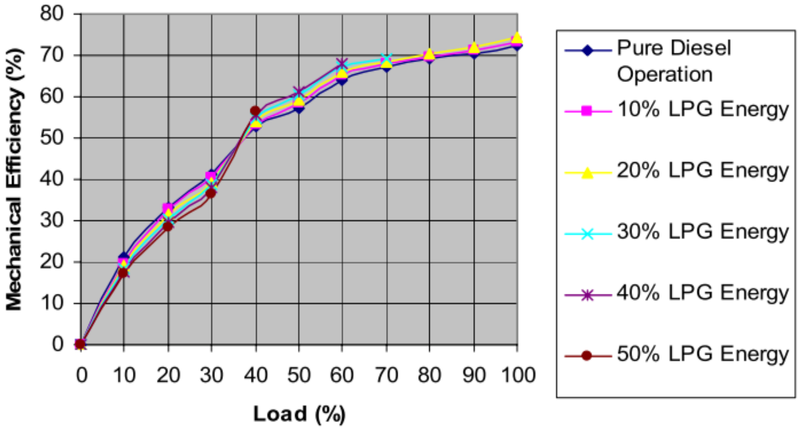

Figure 1. Load (%) Vs Mechanical efficiency (%) [37].

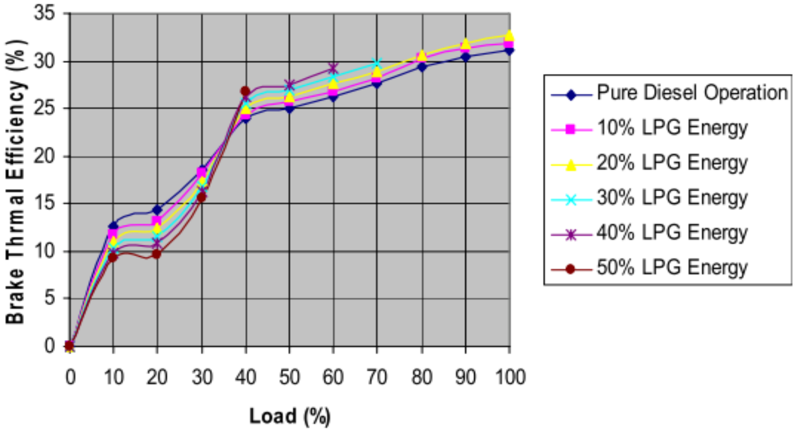

Figure 2. Load (%) Vs Brake Thermal Efficiency (%), using different LPG-Diesel mixtures [37].

Alam [38] explored more into the performance analysis of a DE that is using DI method and running exclusively on only LPG as primary fuel without any diesel content, LPG-Diesel was studied as well. Given that LPG's known to have lower cetane value compared to other fuels, the study introduced two additives: aliphatic hydrocarbon (AHC) and di-tertiary-butyl peroxide (DTBP), the need for these additives is to increase the cetane value. This enhancement facilitated steady DE running across varied spectrum of engine loads. Therefore, to investigate the outcomes regarding varying AHC and DTBP concentrations, the study was conducted with different LPG-Diesel blends. The experimental findings suggest that improving the CN in LPG can be achieved through mixing DPTP and AHC, which considers as reliable approach for operating a direct injection diesel engine. Furthermore, it is feasible to introduce an LPG-diesel blend for running a DE which uses DI system across different engine loads. Additionally, when compared to a diesel-powered engine, it was observed that LPG engine had significantly higher thermal efficiency that diesel.

Mohsen et al [39], the performance of DE while using LPG-Diesel was investigated. This involved modifying an injection system for single-cylinder diesel engine for experimentation, incorporating a gas adjustment valve to supply a mixture of 5 L/min, 10 L/min, 15 L/min and 20 L/min of LPG and varying the load and compression ratio with constant speed at the intake manifold. The results were verified using numerical software, which shows that using

LPG has reduced BTE and the exhaust temperature, while brake specific fuel consumption BSFC has increased. Additionally, the study revealed that for more percentage of LPG the decrease of CO is between 16.6 to 18%, and HC decreased by 8% while using LPG of 15 L/min as well as NOx.

Egence [60] experiment focused on the integration of the LPG fuel in DE. This study involved the installation of an injector mounted at the inlet manifold which provide LPG with specific flow rate based on the cylinder need, utilizing LPG ratios of 25%, 25%, and 10%. The experiment employed standard LPG equipment, including a tank, regulator, LPG filter, and rail, to supply gas to the injector. Pressure was carefully controlled within a range of 200 to 1600 bar to assess injector behavior and combustion quality variation relative to pressure. Output pressure was managed through a pulse width modulation (PWM) signal that controlled the injector plungers, and a pressure transducer was installed for feedback.

The most significant enhancements in DE torque, SFC which is specific fuel consumption, engine power, and other parameters were observed when employing a 25% LPG blend. additionally, the outlet emissions noticed to be decreased such as HC, NOx and other emissions which were observed across all LPG ratios, while there was an increase in CO_2 and CO emissions. Furthermore, using dual-fuel operation the utilization of an electronic injection system proves to be enhancing combustion quality within the engine.

In the context of LPG in its liquid phase, the process involves the mixing of LPG with diesel and subsequent injection into the cylinder via a high-pressure pump. This mixture is then injected at noticeable high pressure using a conventional diesel injector. As the LPG has relatively lower boiling point in its liquid phase, it readily transitions into a gaseous phase upon injection into the cylinder. This rapid evaporation of LPG within the Diesel-LPG mixture can result in improved fuel spray atomization. However, it should be noted that the more concentration of LPG in the mixture the less CN obtains for the fuel, thereby causing ignition delay. Additionally, for less heating value of dual fuel and less latent heat of evaporation of the LPG-Diesel mixture, this contributes to a minor increasing value of ID. Additionally, high primary fuel of LPG percentages within the mixture may also induce engine knock [40-33].

Cao [41] performed and experimental research aimed at evaluating, comparing, and analyzing the performance for mixed LPG-diesel using conventional diesel engines. The fuel mixture was injected into the cylinder at pressures ranging from 180 to 260 bar, with LPG ratios of 10% and 30%. The test results indicated that as the LPG ratio increased, the engine power experienced a small drop in its power, while on the other hand, fuel consumption remained relatively unchanged. Additionally, engine power and torque remained nearly constant when using varying fuel ratios under a consistent speed setting. Moreover, noticeable decrease in NOx, CO, smoke, and other exhaust emissions were detected at maximum load, noticing that the most optimal emissions achieved at a 30% LPG blend. Nevertheless, it has been noticed that HC values increased as expected, while the best HC emissions results obtained while using 100% diesel fuel.

In their research [19], D.H. explored the engine performance and emission results for CIE using LPG-Diesel in DE. Experiments were conducted with fuel ratios of 10%, 20%, 30%, and 40%, using a single injector, while varying the speeds range between 2000 to 1500 rpm, on 90% of the engine load. Thus, the results show that increasing the LPG ratio resulted in decreased engine internal pressure. Additionally, NOx reduced significantly, but as expected that HC was more than normal operation at both speeds as LPG percentages increased. Therefore, this was due to lower temperature of the cylinder mixture during mixed dual fuel running at lower loads, combined with aromatic hydrocarbons inside LPG mixture that were difficult to burn completely. However, modifying the injector could substantially reduce the presence of residual dual fuel mixture at the engine walls, thereby decreasing HC amount at the exhaust. Smoke emissions decreased progressively with increasing LPG percentage, with the best results achieved at a 40% LPG ratio.

Ma et al. [8] studied the impact of fuel injection timing on running DE and engine exhaust results. They converted a conventional DE into a DI LPG-diesel engine that works on dual fuel, and it was tested at fixed speed of 1600 rpm using different engine loads starting with 500 till 1500 W. Thus, results demonstrated that engine output power increased by advancing the mixture injection time. Therefore, for low load with medium-speed conditions, advancing the injection time mitigated the decline in output power typically observed in conventional DE while using dual-fuel. Specifically, at medium-speed and low-load conditions, the brake power of the engine is enhanced by advancing the time of the mixture injection for specific range.

Brake specific energy consumption (BSEC) was evaluated for various operating conditions at medium and low loads which is also considered as the opposite of fuel conversion efficiency. Under low-load conditions, the BSEC decreased till 16 MJ/kWh, representing a nearly 13% reduction compared to normal BSEC of DE without any other alternative fuel. Furthermore, BSEC decreased by almost 11% compared to conventional DE using medium engine power. A lower BSEC value indicates enhanced efficiency while running on LPG-Diesel mixture because of the increased flame velocity and extended ignition delay. Additionally, delaying the injection timing of the fuel resulted in a decrease of the peak engine pressure for single cylinder, and decrease on the peak mixture temperature, and decrease NOx as well. Conversely, it led to an increase in combustion stroke cycle duration, and some emissions were increased such as CO, HC, and smoke.

Emissions Characteristics

Hydrocarbon (HC)

For LPG fueled HCCI the diesel engine shows significant increasing results of non-burned hydrocarbon HC while operating at different engine loads. At higher loads the HC decreases to 15 g/kWh, where the intake air temperature is 50 ^{o}C, yet it's still more than the diesel engine emissions. Moreover, when operating at lower loads, the air to fuel ratio is decreased significantly, and this dilution is causing the HC to increase because of the unproper combustion of the mixture gaseous fuel.

For coated and uncoated DE consuming blend of LPG and diesel as a primary fuel, due to improper burning of fuel, thus, HC will increase compared to normal diesel fueled engine [27], although the LPG-biodiesel shows better results than LPG-diesel fuel, and that is due to the increasing temperature of the engine walls of each cylinder, also due to the higher fuel mixture temperature in the coated engine, also biodiesels fuel is having more cetane number compared to the conventional cetane values, this result was using DTBP additives to enhance the burning inside the combustion chamber [42].

Using modified CI single cylinder DI engine to work with LPG-diesel as primary fuel, results shows that while operating at lower load it will lead to incomplete combustion and due to that HC will be higher than pure diesel engine, while when increasing the loads more than 1 KW for the brake power P_b, the HC emissions is less than pure conventional diesel engine and that is because the combustion is not complete and the fuel blend didn't mix and ignite fully as required [43].

Additionally, precise percentage of LPG-diesel used consisting of 50% for each of propane and butane for LPG, while LPG percentage had a range between 0% to 75% in the mixture, the results indicated that on the previous percentage of fuel blends, HC concentrations tends to rise rabidly starting with 12 ppm and till it reached to 715 ppm on the different mixture ranges, also, the angle where the injection of dual fuel from BTDC which means (before the top dead center) of DE cylinder is having big effect on the final emissions results, for example and advance angle once it's changed to 16° with reference to crank angle CA of DE BTDC, its reduced to 10 ppm to 399 ppm [44].

With modified CI engine working by Diesel-LPG mixture, at the beginning, fuel injection starts with 5000 µs without considering any loads in the calculations, then the period of fuel injection increased from 2500 µs till it reaches 15000 µs, the results shows that the emissions was higher compared to conventional DE, specifically HC where it shows more values along most of the LPG fuel injection with different injection durations as stated before. Therefore, the main purpose regarding these increasing values is the lower temperature which mainly accumulates inside the combustion chamber of the engine along with other reasons like crevices, poor lubrication, etc. but the main reason here is the incomplete and improper combustion of diesel-LPG blend mixture [45].

Nitrogen Oxides (NOx)

NOx forms because of the high temperature inside the engine, for LPG fueled HCCI the engine shows that NOx decreases over all the different range of loads, for 50% the load decreased by 75% when comparing it to the normal standard naturally aspirate engine. At full load NOx for diesel engine increasing by 60% compared to HCCI engine, that's due to the combustion in DE which led to have the peak pressure to increase consequently temperature will increase within the internal enclosed area of the cylinder and the engine heated walls during combustion process will be resulting in more NOx formation [31].

For coated diesel engine using LPG-diesel as a fuel, NOx emissions increase noticeably with respect to the higher value of DE power, instead, using LPG-biodiesel with additives such as DTBP leads to almost same results of NOx emissions compared to uncoated diesel fueled engine, moreover, NOx emissions also could be reduced because of other important fuel characteristics such as density, viscosity and high latent heat of evaporation for this type of additive DTBP which remarkably decrease NOx emissions, this is because of the improved cetane number through adding DTBP additives and by ignition time delay which enhance the mixing and fuel burning and increasing the engine combustion efficiency [42].

Furthermore, considering same study on DE with conventional DI utilizing LPG as main engine fuel along with ignition enhancer additive which is (DDE) Diethyl ether as an ignition enhancer, it shows that NO emission decreases, many reasons contribute to this reduction such as temperature of self-ignition for LPG that is different than normal diesel temperature, reducing inlet air and increasing ID which results in reducing the temperature inside the cylinder. Also, the experiment shows reduction in NOx emissions using LPG-diesel fuel, and the more LPG flowrate is used the less NOx emissions produced [42]. Although adding DDE increases NOx emissions, latent heat of evaporation as mentioned earlier contribute effectively where high value for DEE lowers the emissions of NOx, this is controlled by ID while using DDE [27].

Furthermore, an experimental study using modified CI engine shows that NOx increases at lower engine loads more than pure diesel engine while using Diesel-LPG mixture, while on higher loads NOx values decreases compared to the pure diesel operation [43]. Also, similar experiments show noticeable reduction of NOx on different loads [30].

NOx reduced from 363 ppm to 80 ppm for LPG-diesel engine consisting of 50% for each of propane and butane for LPG, the reduction of NOx formation because of reducing the volume of oxygen required to form unwanted gaseous through proper ID of the fuel injection, the diluted oxygen inside the engine cylinder reduce the temperature as well. Moreover, once the angle of fuel port injection is changed from the original position to make it 16° CA BTDC, NOx increases 3.6 to 8.4 times [44].

With modified CI engine working by LPG-diesel dual fuel, NOx emission reduces significantly with all the LPG injection duration scenarios starting with 5000 μs until 15000 μs on most the lower load scenarios and semi higher load ranges compared to conventional DE. Furthermore, when operating near 82% of the engine load, it can be noticed that NOx values are more than standard DE. Thus, regarding the reduction of NOx emissions, it is because of different parameter that could affect it but mainly two reasons contribute the most, the first one is the low engine cylinder temperature, the second one is that there is not enough oxygen in the combustion chamber because it has been replaced by LPG as dual fuel with diesel [45].

Carbon Monoxide (CO)

CO considers as invisible gas which has neither color nor smell. This gas can have a sever effect on humans, CO is inhaled by the lungs and then transmitted to blood stream this can cause asphyxiation which will affect the function of different organs [46]. Carbon monoxide results from lack of chemical reactions where the oxidization process does not occur completely which is due to the incomplete air-fuel mixture combustion. As known within DE operations the carbon atoms will convert to CO_2 if fuel to air mixture is properly done and perfectly combusted, but for this case as air is less and the reactants fuel and air compositions didn't mix properly it results in come unburned atoms which results in CO formation.

Saleh, H.E. [47] studied the emissions of DE while using LPG-Diesel as main primary dual fuel, also discussed the carbon monoxide emissions and engine load. The largest production of carbon monoxide occurs due to the incomplete combustion for air to fuel mixture which is mainly coming from the low availability of oxidant, or low gas temperature. Moreover, when operating the diesel engine at full capacity, there is a notable rise in CO emissions linked proportionally to the higher DE load, that's because the increase of rate for injection per cylinder for each stroke, where the fuel is timed to be injected in specific period so it will mix and combust correctly, in this case the injection is not properly timed which results in incomplete combustion due to the higher fuel/air ratio [34]. Hence, when comparing this dual fuel to conventional DE using only diesel, it is known to be producing more quantity of carbon monoxide CO while operating DE using LPG-Diesel as the main dual fuel. During partial loads of operations, the cylinder contains less fuel, leading to improper blending of fuel/air, also improper mixing and combustion of the mixture, thus, as mentioned before this results in minimal CO oxidation, which leads to reduce the conversion to CO_2 and increase the CO emissions [48]. Yet, for higher engine loads, there is a noticeable reduction in CO concentration because of the more intake of air-fuel ratio and the combustion occurs faster as well. Thus, this elevated combustion rate raises temperatures of the cylinder interior and enhances oxidation reactions, ultimately leading to reducing the carbon monoxide along the exhaust gaseous.

Furthermore, The study discussed the different LPG mixture quantities and their effect on the outcome emission of CO while varying the loads from 10% to 100%, Fuel#1 is the pure propane, the second #2 with 10% LPG, the third #3 with 30% LPG, the forth #4 with 50% LPG, and lastly fuel #5 with 70% LPG, thus, the final analysis stated that with increasing the concentration by 30%, 50% and 70% in the mixture higher CO in the exhaust emissions produced specifically at lower range of the load, the results shows that 1.3% produce 3140 ppm of CO , 6.5% produce 3300 ppm of CO, and 19% produce almost 3700 ppm of CO at 25% of engine low load. As discussed in the study, once increasing the load to the maximum, many factors can contribute to CO emissions such as, lower flame temperature of LPG mixture, lower flame speed, higher carbon to hydrogen percentage and longer ignition delays, thus, the more LPG in the fuel mixture the more CO emissions will be produced compared to pure LPG fuel [49].

Smoke

Mustafa Aydin [50], investigated the major relation between diesel-LPG on DE performance along with its greenhouse exhaust emissions. the below Figure 3 is showing the LPG to diesel percentage and their smoke emissions at different engine loads starting from 500 to 1500 watt, from chemical composition perspective it can be stated that LPG is considered better fuel normal pure diesel because it can mix easier with air due to its low value of carbon content which reduce the high-rate emission possibility during combustion.

Also, From the graph below it can be observed that at all different loads that the same trend is occurring where the increase of LPG percentage always reduces the smoke emissions significantly, the main reason is that the C/H carbon to hydrogen ratio is lower for LPG compared to diesel. Although this lower C/H contributes to lower energy efficiency, LPG-Diesel dual fuel will produce lower smoke emissions when operating at different engine loads compared to conventional diesel engines.

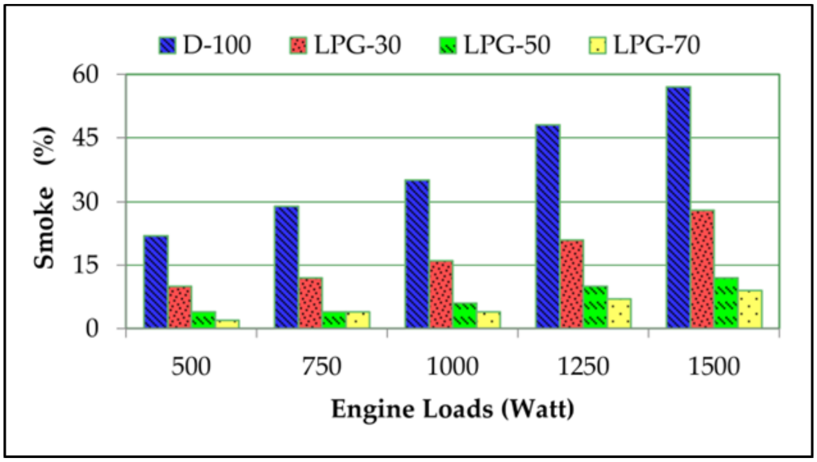

Figure 3. Engine Loads (watt) Vs smoke emissions (%) using different LPG-Diesel mixtures [50]

Engine Performance and Combustion Characteristics

Torque

One of the methods used to reduce NO emissions and saving the consumption of the fuel is ICSI which represent in-cylinder steam injection, using precisely injection timing, LPG could be benefited, the injection starting from 30 mg of steam till 120 mg, it can be observed at all cases that with more steam injection the less torque it requires at the same operating conditions, till it reached higher load of 1200 rpm then the torque reduced for all different cases. [15]

Brake Specific Fuel Consumption BSFC

The BSFC is decreasing considering low range with engine load between 800 to 1200 rpm and for more steam injected, the engine fuel combustion become less. The decrease in BSFC value is coming from the increasing engine power that comes from higher speed, also, regarding DE thermal efficiency for the cycle it is enhanced. By using ICSI method at speed range of 1200 to 1600 rpm as medium, and high speeds above 1600 rpm, the trend shows an increasing value for the engine BSFC. Furthermore, it can be noticed that the combustion inside the cylinder become worse as the mass of steam injection gradually increases from 30 mg to 120 mg, this is the key factor for improperly mixed atoms of fuel which didn't react to leave the combustion chamber to the exhaust without transforming into useful work that is added to the brake power. Consequently, as mentioned earlier that the engine combustion efficiency will be reduced when C/H is reduced, and this will change the value of BSFC higher. [15]

Brake Thermal Efficiency BTE

As shown in Figure-4 that LPG in HCCI is having more BTE while considering different loads starting from 1 to 6 bar as brake mean effective pressure BMEP, this experiment is done at 50 C for the intake manifold of air, and it's compared to pure diesel as primary fuel. Moreover, this increase in the BTE is affected by the preheating area at the beginning of the intake manifold, this is occurring by a phenomenon which makes faster spread of the pre-flame reaction at the beginning of the combustion process. One advantage for this experiment is using preheater for the intake manifold which enhance BTE through faster and enhanced pre-flame mixing and combustion reaction.

Higher BTE values up to 25% observed for all the loads and then the difference has been plotted against different fuels of DE. The study also shows that almost 80% of the load an improvement of engine efficiency occurred around 4.5%, this is possible due to using additive for example DTBP which makes is mixed with LPG-biodiesel dual fuel, this additive works as anti-NOx additive. [42]

A study on modified diesel engine working of LPG-Diesel shows that LPG-diesel dual fuel mixture always enhances the DE performance and efficiency by 3% compared to conventional DE. [43]

Another study shows that using pilot diesel fuel which is A microprocessor fuel management system along with LPG as main fuel helps to enhance the BTE with 20% more. Moreover, diethyl ether (DEE) was used in direct injection DE to improve the ignition. This improvement in BTE may be because of many reasons such as the elevated in-cylinder temperature of air/fuel, along with delay period of the pilot which might affect the BTE. [27]

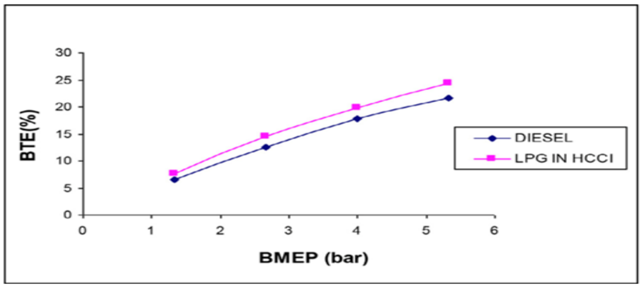

Figure 4. Brake Thermal Efficiency Vs load (bar). [31]

Exhaust Gas Temperature

One of the important factors to measure for DE characteristics is the exhaust gas temperature of the engine, thus, for DE system the results show higher values at all loads during engine operation as shown in Figure 5. Thus, approximately 20% drop was measured for the exhaust gas temperature for LPG in HCCI with respect to normal diesel combustion operation, this drop is due to the lower internal temperature for the cylinder compared to conventional DE results, while in HCCI combustion the temperature of the exhaust drops down. Therefore, the range for the exhaust gas temperature in diesel operation varies from 230 C up to 520 or 530 ºC, where in the other mode it varies from 200 ºC to 490 ºC. [31]

A study on coated engine stated that the temperature at the exhaust is reduced for all verity of loads during the experiment when comparing it to any different test fuel, this experiment done on LPG-Biodiesel with inhibitor or modifier which is DTBP. [42]

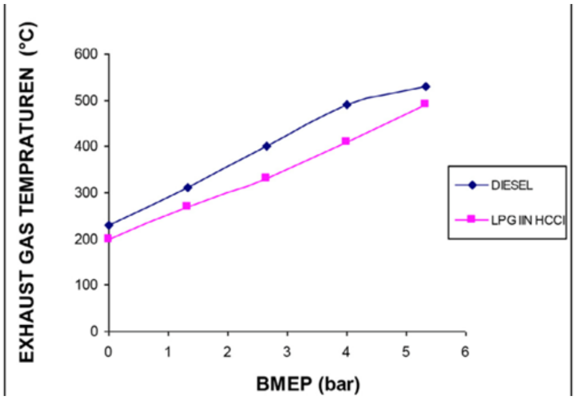

Figure 5. Brake Thermal Efficiency Vs load (bar) [31]

Heat Release Rate

One of the characteristics to be studied is rate of the heat release rate at certain CA of the piston rotation, in the below figure 6 it shows the comparison between normal diesel engine and LPG in HCCI, for HCCI mode the maximum heat release occurs with 75.9 J, which is around 183° CA and the diesel mode is having higher heat release at the same angle of 85.7 J/ ° CA, As shown from the below figure 6 that LPG engine which works using HCCI release less heat because it has higher auto ignition temperature which is due to the early start of combustion process almost starts 4 ° CA before normal diesel engine. Therefore, upon comparing the mixing of air to fuel results with LPG-fuel, the mixture of LPG gas shows better combustion results while introducing higher intake air temperature [31].

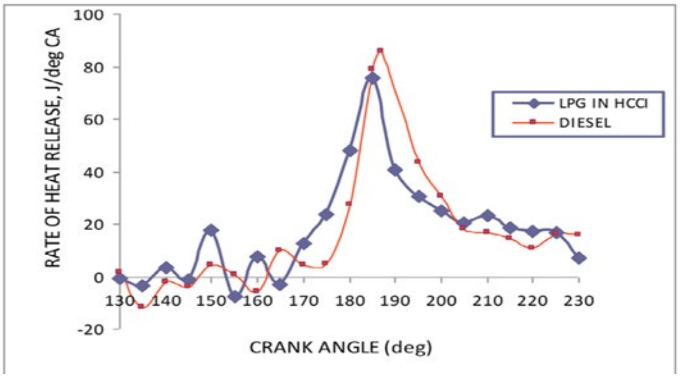

Figure 6. Heat release rate. [31]

Ignition Delay ID

Ignition delay ID is an important factor for the engine cycle synchronization which ensure proper combustion process, a study shows that mixed LPG and HVO leads to change ID of pure LPG to lower value. there are different mixtures between LPG and HVO, noted that the mixture of 75 HVO and 25 LPG can operate on normal DE without any changes on the design of the engine, also with using same original injection system with no changes. Additionally, the experiment shows the difference of fuel reactivity for low which is LPG, and high reactivity, which is HVO while mixing them together, and this ratio can be balanced for the fuel range to operate normally during engine running period. Thus, the best way to control the mixture and the ration of LPG to HVO while operating is to use injection system that manage the mixture through in-line mixing valve, and all this will be controlled by engine control unit (ECU). [14]

Brake Specific Energy Consumption BSEC

BSEC is better way to calculate the energy required for an engine specifically for dual fuel engines as shown here in this experiment where diesel and LPG or Biodiesel is used, it's preferred to use BSEC than the BSFC [51] normal diesel operation is the higher energy consumption, and it can be noticed that BSEC for all the loads from 20% to 80% is less than diesel fuel operation, three mixtures shown which are Diesel-LPG, and Biodiesel-LPG, and finally Biodiesel-LPG using additive DTBP which is the lowest in terms of BSEC, Also, the decrease in BSEC further improved for the entire load spectrum once the load increasing [42].

Improving the Combustion of and Emission of LPG-Diesel Dual Fuel

Using Hydrogen H_2.

Many studies show that using hydrogen H_2 addition into dual fuel could enhance fuel properties and it will deliver solutions to many problems such as: increasing ID, producing high unburned mixture, due to uncontrolled combustion reaction rate and knocking, the engine durability will be affected [52, 53, 54, 55]. In addition, several studies shows that there is a need for more improvement in terms of dual fuel using hydrogen where there are big area of improvement and research not discovered yet, also, the engine which work on hydrogen and LPG as dual fuel requires specific lubrication for the engine cylinder, this special lubrication need to be further studied as well [56].

Results shows that H_2 addition reduced ID, which gives the mixture faster combustion, accordingly, rising the pressure of the DE inside each cylinder that works using H_2. Moreover, high flame speed of H_2 observed which results in faster combustion leading to better fuel–air mixture and ignition. Also, BTE was improved at all different loads.

For emissions, using LPG as dual fuel shows the released emissions of HC and CO has been increased significantly when comparing it with the baseline normal condition, where the LPG/diesel dual fuel blend emissions become better than normal once H_2 enhancer added to the system. Moreover, NOx increases because of the pressure within the engine cylinder which increases with the temperature as well, accordingly, this makes the flame temperature to increase. Also, the concentration of HC decreases while adding H_2 to the LPG–diesel dual mixture. As well as huge reduction in soot emissions was observed while adding H_2 to the mixture [57].

Different loads presented 10%, 40% and 80% with respect to maximum pressure of the DE cylinder using bar unit. Therefore, the maximum pressure for each cylinder for hydrogen at 10% load and 30% hydrogen substitution slightly increases compared to LPG, while on 40% load it increases as well, this is because of the increased value of ID of LPG/Hydrogen as dual fuel. Also, at 80% of the load the pressure inside the cylinder for the hydrogen is found to be less than LPG as fuel. In general, the main reason for the slow combustion rate and low pressure occurs due to the fuel/air ratio lean blends inside the cylinder, this means that the fuel is less than the required ration which means that the gaseous phase of this mixture inside the cylinder will delay and make the ignition weaker, and the pilot ignition is weak, thus, that's why this issue occurs and mostly it's happening at low operation loads.

With a composition of (LPG: hydrogen = 70:30), overall heat release rate decreases. however, at certain range of CA around 380 deg the LPG with diesel the heat release increases at certain range with different engine loads but the heat release reduced for first part of engine combustion, and it reaches around 34.54 J/deg CA, this is because of sluggish combustion, and other reasons regarding the mixture concentration like in the lean blends sluggish flame spread is affecting the heat release. Also, different mixtures between diesel + hydrogen or diesel + LPG shows different results of heat release [58].

Using DTBP

One of the main important secondary fuels in dual fuel field while using LPG-biodiesel mixture is (Di-Tertiary Butyl Peroxide) DTBP which helps to obtain larger brake thermal efficiency BTE at different engine power values when it's compared with other dual fuels such as the ones discussed earlier. As DTBP considers as anti-NOx additive, it reduces the NOx emissions significantly when used in dual fuel engines.

Also, using DTBP reduces BSEC more than normal operations, this is because it enhances the mixture of fuel to air inside the cylinder which gives better mixing and burning during the combustion cycle. Furthermore, one of the main reasons for ID reduction is the high cylinder temperature as discussed earlier, that's why the exhaust gas temperature is getting lower temperature from the exhaust manifold while using cetane improver additives.

For the emissions, CO reduced among all the different engine power range, that's because of the enhancement in the combustion cycle where the oxidation takes place and reduces the CO emissions. HC found to be decreasing using DTBP as additives compared to normal operation without additives, and It's found to be close to the diesel operation, this could result from the increased temperature inside the engine cylinder walls and gas temperature and higher cetane number provided by the additive. For NOx it was lower than other cases of dual fuel mixtures, and almost like the diesel operations, due to the great value for latent heat of evaporation of DTBP additive which may decrease NOx outcome emission significantly. Low exhaust temperature results from better fuel burning inside DE and higher value of the combustion efficiency, and it's due to ignition time is retarded which produces lower NOx eventually [38].

Using Hydrotreated Vegetable Oil (HVO)

HVO is an interesting fuel used in the diesel engine for many courtiers, blends of LPG-HVO were experimentally tested in the modified Diesel Engine DE by modifying the injection system of the new dual fuel, at various and wide pressure and temperature range this new system has been installed with three different pilots, first one without pilot, second one using one, and the third system using two pilot injection for DE. The main reason for this modification is to have compatible injection system that can reduce the high ignition delay ID of LPG. Thus, mixing LPG with this fuel HVO helps to decrease the ID of DE working by only LPG. Also, the study shows that 25% LPG + 75% HVO mixture could be used in heavyweight DE with no extra modification or any special design change or new injection methods to be used in the engine [14].

Furthermore, results show that operating the DE with these modified injection system strategies leads to decrease ID from LPG-HVO blends. Moreover, the experiment also shows that using two pilot in the cylinder as injections gives the better results in decreasing the ID which gives better results that using only one as injection. In addition, these modifications on the injection system and new experiments on DE dual fuels such as LPG-HVO or even LPG-diesel allows new studies and technologies to reduce GHG emissions [28].

Using Aliphatic Hydrocarbon (AHC)

One of the important additives to dual fuel is aliphatic hydrocarbon (AHC) as it's used for various purposes but mainly for LPG experiments as they have lower cetane number than normal fuel, so AHC works on improving the cetane number to match the engine operating range, as mentioned earlier that providing the engine with suitable fuel that have appropriate cetane number is enhancing the engine stability while operating at wide range of loads, several different LPG-diesel mixtures were obtained and tested experimentally by changing the quantity of additives such as DTBP and AHC [38]. Moreover, regarding the exhaust emissions, smoke and NOx found to be reduced significantly when the different mixtures of LPG-30%, 50, 70% was used. along with the additives AHC and DTBP [50].

From figure 7 the different mixture shown using LPG as dual fuel with different percentages and it could be noticed from the figure that BSFC was lower for the higher amount of LPG added with 70% as primary dual fuel with diesel and among all different loas at 1000-Watt was the lowest value which is the best operating condition for this dual fuel experiment, which is approximately 282 g/kWh. Therefore, the main reduction of BSFC is due to lower heat value or it's known as calorific value QLHV while using LPG was more than conventional diesel fuel [50]. Moreover, Similar studies shows the same results for BSFC for dual fuel and the advantage of additives on it. [37, 47, 59].

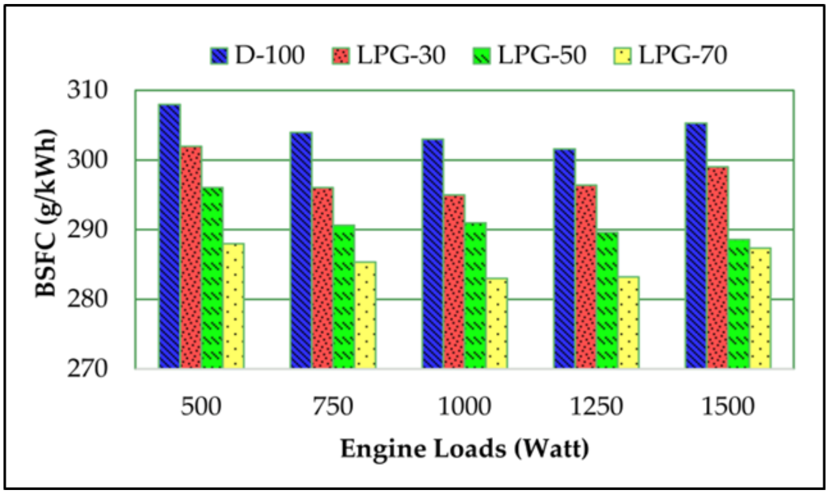

Figure 7. Brake Specific Fuel Consumption (BSFC) Vs engine loads [50].

Using Rapeseed Methyl Ester RME and GTL

As shown from figure 8. That RME shows the lowest total CO and HC emission as shown in part (a) and (b) which are showing the results over all the DE conditions with different loads and the comparison with ultra-low Sulphur diesel (ULSD), the low values are because of rich oxygen content in the fuel tip nozzle or fuel spray that gives the mixture better oxidation results, and it helps in better mixing through better fuel penetration.

GTL has more hydrogen to carbon ration H/C and as discussed previously that this ratio is important for the emissions and efficiency, also, it has more volatile attached with H_2, it helps in reduce the carbon-contained emissions. Due to its high cetane number, high ignitability helps to decrease the value for the outcome emissions. Moreover, as presented in fig 36. (b) and (c) that the quantity of emissions specifically the smoke in non-aromatic fuel which is GTL was lower than the conventional fuel, which is ULSD without LPG addition, but for the oxygenated fuel case which is RME it was higher. Note that NOx emissions show more values when using RME and the value decreases with GTL in both graphs (b) and (c). For the previous part, smoke meter utilized to measure quantity of small particles of soot at the outlet manifold of DE, then, the outcomes were presented by using filter smoke number (FSN) complying with ISO-10054 standard.

Therefore, Rapeseed Methyl Ester RME is used as injection port or pilot as discussed in this paper for the LPG-Diesel dual fuel. Along with H_2it improves thermal efficiency and reduced exhaust emissions except for NOx. Furthermore, for GTL dual fuel with diesel, it improved soot-NOx trade-off, in fact NOx increasing during the combustion of RME where GTL reduce it. From GTL properties, many factors are discussed such as fuel deterioration in different cases of regulated and unregulated outcome emissions at the exhaust, along with their thermal efficiencies which was determined in the study as well [57].

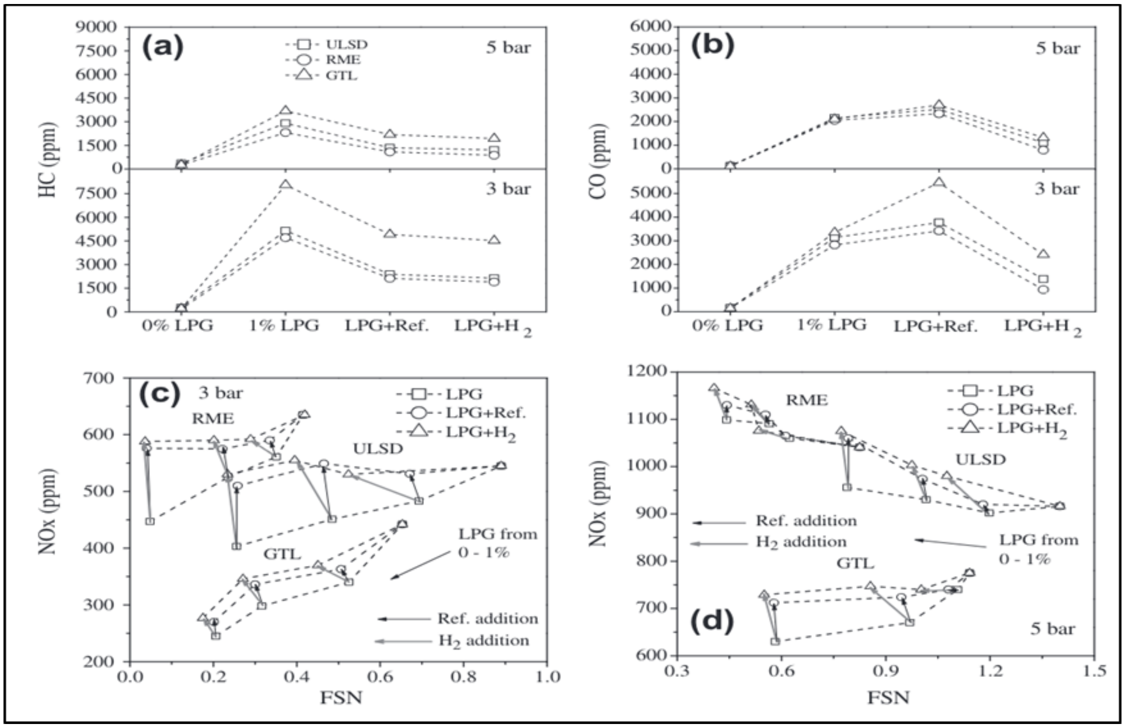

Figure 8. Exhaust engine gaseous emissions Vs FSN for three fuels with additives [57]

Critical Review Summary

Researchers recently focuses more on alternative fuels targeting to reduce the focus on the fuel and energy consumption through fossil fuels, and ultimately the aim is to improve engines performance and combustibility of CIE's and minimize the unregulated emissions and the diesel combustion which affects the environment and reducing high noise levels as well. Liquified petroleum gas has been used as primary fuel along with diesel in CIE's, LPG-Diesel is fuel-efficient choice, it had relatively attractive cost and it considered as clean fuel which had lower greenhouse gas GHG emission. The summary of the most critical literatures done on LPG-Diesel dual fuel presented in this review is summarized below:

1- One of the major weaknesses of LPG alone as only primary fuel source at diesel engine without any other dual fuel is it's poor autoignition performance, alternatively, mixing LPG with diesel as reactive fuel enhances the fuel characteristics and moving it to the acceptable range of operations. LPG can be blended with HVO to have higher cetane number.

2- LPG is lighter than diesel so their densities are different for the same amount, thus, fuel tank should be bigger to obtain same driving distance. Also, using dual fuel shows significant reduction in ID when using two pilot injections than one, which reduces the GHG emissions.

3- In gas phase, the formation and mixture of LPG-Air at the inlet showed that emissions such as NO, soot, and smoke could be decreased noticeably. In comparison with conventional DE operation engine using single fuel, LPG-Diesel results shows that engine characteristics for example specific fuel consumption, power, torque, and other parameters were improved, while injecting LPG as gas from the intake port it shows that NO results decrease significantly along with smoke emissions. Moreover, because of using the dual fuel LPG-Diesel, the engine characteristics also improved such as torque, SFC, engine overall outcome power and more. knowing that power and torque were increased by 5.8%.

4- In liquid phase, LPG-Diesel mixture injection into the cylinder shows slightly reduction in engine power, and fuel consumption almost the same. Many emissions reduced noticeably such as NOx, CO, smoke, and others, this as at maximum load of DE operations, noticing that the optimum results of emission such as NOx, smoke and CO obtained by mixing %30 LPG and 70% diesel, simultaneously, the amount of hydrocarbons HC emissions increased.
5- For LPG fueled HCCI the diesel engine shows significant increasing results of unburned hydrocarbon HC at different loads. And because of the bad mixture and combustion of dual fuel gaseous at lower loads HC found to be increasing, the main reason is because of low concentration of air to fuel ration mixture which reaches to 135 g/kWh compared to less than 10 g/kWh in only diesel fueled engine.
6- For LPG fueled HCCI results shows that NOx decreases over all the different range of loads, for 50% load the decrease compared to naturally aspirate DE is almost 75%, and at full load NOx for diesel engine is 60% higher.
7- The CO concentration decrease gradually with increasing engine load for dual fuel of LPG-Diesel.
8- Increasing LPG percentage of the mixture in dual fuel causes different emissions to behave differently from the reference diesel engine emissions, for example, smoke reduced significantly because the low C/H percentage.
9- For combustion characteristics, BSFC decreases at low speeds using LPG as dual fuel and by ICSI method, also engine performance parameters have been reviewed such as BTE and exhaust gas temperature increases for LPG in HCCI mode.
10- Heat release rate is less at its peak when compared to normal diesel operation, while ID is reduced using LPG-HVO mixture with 75% for LPG.
11- BSEC decreases for wide range of loads compared to different fuels, and further decrease observed while using DTBP additive, where highest effective efficiency observed while mixing 70% of LPG and operating at 1250 W on DE.
12- An important part for improving the combustion and emissions is additives, there are many different types of fuels and different additives could be added to the LPG-Diesel dual fuel mixture, such as hydrogen, AHC, HVO, DTBP, RME and GTL.

For future research opportunities on LPG-Diesel dual fuel, a promising experimental study could be conducted on developing a modified prototype for Constant-Volume Combustion Chamber (CVCC) engine which will be attached to similar DE injection system that works on the dual fuel LPG-HVO or LPG-Diesel mixture as well as having variable injection control system which is capable of handling various injections [28].

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