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A Review of Effect the LPG Fuels Addition on the Emissions and Performance in Compression Ignition Engine

Radhwan Ali, Nuraini Abdul Aziz and Abdul Aziz Hairuddin
Department of Mechanical Engineering, Universiti Putra Malaysia,
43400 UPM Serdang, Selangor, Malaysia

Abstract: Towards the effort of reducing pollutant emissions, especially nitrogen oxides and smoke from diesel engine Direct Injection (DI), engineers have proposed various solutions one of this solutions are uses of the gaseous fuel as a limited addition for liquid diesel fuel. The utilization of alternative gas fuels like Liquefied Petroleum Gas (LPG), Natural Gas (NG), etc. is a promising approach in decreasing the dependence on petroleum-based liquid fuels and decreasing emission from a diesel engine. Therefore, using Liquefied Petroleum Gas (LPG) as an alternative fuel is an optimistic solution. The potential profits of using LPG in diesel engines are both economic and environmentally friendly. The high auto-ignition temperature of LPG is a serious principal since the compression ratio of normal diesel engines can be sustained. Therefore, the challenge currently faced is to reduce the exhaust emissions without making any major changes to their mechanical configuration of a diesel engine. Thus "LPG-diesel dual-fuel engines" are referred to the engines that utilize both LPG fuel and normal diesel fuel. LPG dual-fuel engines can be described as modifies diesel engines that utilize LPG as the primary fuel and diesel as the secondary fuel. At high output, the thermal efficiency of LPG dual-fuel engines is good; however, the performance is lower in part-time load conditions because of poor usage of charges. Therefore, studies show that the utilization of LPG with a diesel engine is among the most effective ways of reducing NO_x and PM emissions.

Key words: Liquid Petroleum Gas (LPG), diesel, hydrogen, engine, pollutant emissions, Natrual Gas (NG)

INTRODUCTION

The energy amount in the world is affected by various factors like the increase in per capita energy consumption, economic growth and the increase of world population. Two main issues are caused by the increase in energy consumption; the first is the rise of energy prices caused by limited energy resources and the second is environmental pollution due to intensive use of energy. Motor vehicles utilize a large part of the global energy consumed. These motor vehicles operate mainly by diesel fuel and gasoline obtained from crude oil that is a formula of energy with limited reserves (Agarwal, 2007). The constantly enhancing energy demands and the limited resources are 2 issues that need to be resolved since they might lead to difficulties all around the world in future (Yamik, 2002). Using gaseous fuel along with the liquid diesel in CI engine is one of the ways to resolve this issue. The utilization of alternative gas fuels like Liquefied Petroleum Gas (LPG), Natural Gas (NG), etc. is a promising approach in decreasing the dependence on petroleum-based liquid fuels and decreasing the CO emission along with other pollutants from a diesel engine (Balat, 2008). Therefore, the liquid petroleum gas LPG is a practical and good alternative gaseous fuel; it is a gas product of petroleum refining and mainly consists of propane, propylene and butane along with other light hydrocarbons (Goldsworthy, 2012; Raslavieius *et al*., 2014). A wide range of diesel engine sizes and types examined at various operation conditions is the focal point in this review. In a similar technique, various LPG percentages were used in the optimization of the engine output. The discussions on emission, combustion and performance characteristics are provided in the different sections in order to provide a clear understanding of the impact of LPG utilization in the diesel engine in the dual-fuel mode.

MATERIALS AND METHODS

Composition of liquid petroleum gas: LPG is a gas that is odorless and colorless and mainly consists of butane and propane or a combination of both in different ratios as a mixture. It is possible to store LPG as a mixture or

Corresponding Author: Radhwan Ali, Department of Mechanical Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

Table 1: LPG composition (volume %) as automotive fuel (Saleh, 2008)

Country	Propane	Butane
United kingdom	100	-
Austria	50	50
France	35	65
Italy	25	75
Spain	30	70
Sweden	95	5
Germany	90	10
Australia	70	30

separately. They exist as the gas at a normal atmospheric pressure and room temperature. The LPG standard is not universally observed. The propane concentration is as low as 50% and as high as 100% at particular locations. There is a significant difference in the usage of LPG as an automotive fuel from one country to another depending on the availability and cost of the fuel relative to alternative fuels; particularly diesel and petrol. The variation in the composition of LPG fuel in a number of countries is demonstrated in Table 1.

Moreover, the LPG composition changes based on its source and having knowledge about the liquid petroleum ga's composition has great importance in the analysis of the differing compositions that have a significant impact on the combustion process in the diesel engine. This seeks to improve the exhaust emission quality while maintaining high thermal efficiency comparable to a conventional engine (Saleh, 2008).

Diesel engine modifications: Configuring diesel engines to run on LPG-diesel dual fuel engine can be done with simplicity methods. In these engines, the LPG is mixed in the air intake whereas in an ordinary diesel fuel it is injected through an injection system with a specific degree of diesel supplied; however at a decreased rate (Ergenc and Koca, 2014; Goldsworthy, 2012). Engine modifications are necessary in order for the engine to work in dual mode through the attachment of an LPG line to the intake manifold beside an evaporator. Through the regulating valve, the gaseous fuel flows into the gas mixer which is placed on and connected to the intake manifold (Bora *et al*., 2013; Paykani *et al*., 2011; Rao *et al*., 2010). LPG is supplied to the engine with accompanying electronic or mechanical controls for different engine speeds and loads. The engine output and combustion process differ based on the type of gaseous fuel supply system and the engine type (port injection or direct injection). The LPG's mass flow rate is in proportion to the difference of the pressure between a gas mixer and the evaporator where the pressure is retained and kept almost equal to the atmospheric pressure. However, in LPG dual fuel engines, it is very crucial to control the pilot diesel and primary LPG's flow rate at various operating conditions of the engine. Performance improvement and smoke emission reduction might not be affected by lower LPG content. Though, much higher LPG content is likely to rapidly enhance the in-cylinder pressure and damage the engine.

Numerous revision proceedings have been carried out in the LPG-Diesel dual fuel engines by various researchers such as the adjustment of single cylinder (Murthy *et al*., 2012; Rao *et al*., 2010) and multi-cylinder (Stewart *et al*., 2007) diesel engines in which the LPG is supplied in the dual fuel mode by manifold injection (Raslavieius *et al*., 2014; Wattanavichien, 2011) and manifold induction (Murthy *et al*., 2012). It was found that the combustion, performance and emission characteristics of LPG-Diesel dual fuel engine depend on the type of the engine, LPG fuel supply system and engine operating conditions.

Emission and performance: Using gaseous fuels together with diesel in compression-ignition engines is thought to be a proper alternative for the existing stationary, maritime and automotive engines. It is believed that economic and environmental advantages can be provided through this application (Ashok *et al*., 2015). As a result, the impacts of using diesel-gaseous fuel dual-fuel engines have been widely examined in various studies. The studies were carried out on carrying test engines with different gaseous fuel types as well as different operating points. These studies evaluate the performance as well as the engine-out emission such as particulate matters, nitrogen oxides, unburned hydrocarbons and carbon monoxide.

Effect of LPG addition on performance: High thermal efficiency can be provided by dual fuel that operates with LPG which is almost comparable to that of the same engines which operate on diesel fuel at higher loads. However, engine emissions and performance deteriorate at low loads in a dual-fuel mode operation. The most important reason for the poor performance at low loads is the induction of significantly lean LPG-air mixtures in a dual-fuel engine case. These lean mixtures ignite with difficulty and burn slowly at low loads. The flame propagation is incomplete in these mixtures and the bulk of gas fresh air mixture remains unburnt which leads to high HC emission and worse brake thermal efficiency (Pirouzpanah and Saray, 2007; Poonia *et al*., 2011).

Moreover, a number of experimental and theoretical investigations were conducted to study an LPG-diesel Dual-fuel engine's performance at different LPG compositions, like propane to butane ratio (Elnajjar *et al*., 2013a,b; Lee *et al*., 2013; Leermakers *et al*., 2011; Saleh, 2008). Saleh (2008) investigated 5 different LPG fuel compositions to understand the impact of LPG-fuel composition on the exhaust emissions and performance of the engine in a twin cylinder dual-fuel engine. Figure 1 shows the comparison between the impacts of different engine loads on the thermal conversion efficiency of the pure propane and different LPG blends in dual fuel operation. It can be observed that the efficiency enhances with an increase in the load for all the different LPG blends. The thermal conversion efficiency of pure propane, 10% butane and 30% butane do not demonstrate any noticeable or obvious difference at full load. Furthermore, Rosha conduct that the thermal efficiency for LPG-diesel at low load was lower than diesel fuel at same load by 11%. However, the efficiency at high load for the LPG-diesel was more than diesel by 29% and he observed at part loads the efficiency was increased in the case of the EGR-operated engine due to re-burning of hydrocarbons that enter the combustion chamber which is illustrated in Fig. 2.

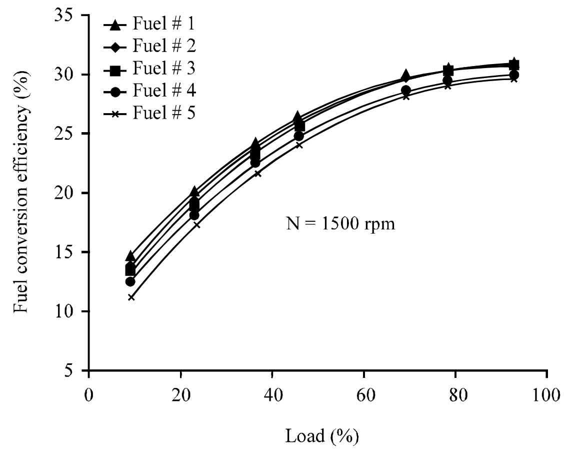

Fig. 1: Variation of fuel conversion efficiency vs. engine load for LPG blends (Saleh, 2008)

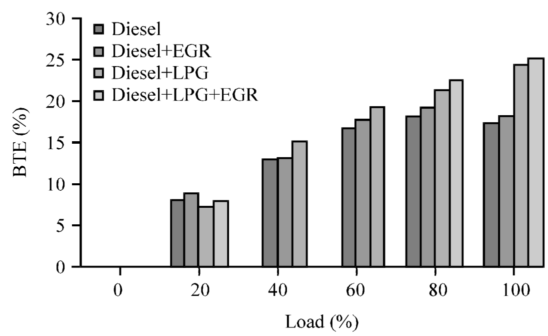

Fig. 2: Variations of BTE vs. load

Fuel consumption: Here, the effect of a dual-fuel operation with a comparison to conventional diesel combustion on fuel consumption is compared. Dual-fuel combustion tends to result in increased carbon monoxide and unburned hydrocarbon emissions. This is a direct implication of dual-fuel operation's worst combustion efficiency which leads to the increase of fuel combustion. However, Amarendar *et al*. (2008) conducted the experiments on a conventional diesel engine operating in a dual-fuel mode using diesel and LPG and found that the brake specific fuel consumption was 30% lower than diesel fuel operation. This could be due to better mixing of air and LPG and improved combustion efficiency. Additionally, Saleh (2008) performed that the duel fuel combustion using diesel and LPG (PFI) did not significantly affect the engine's consumption and efficiency. Generally, at low loads there is a slight increase in particular energy consumption in comparison to the conventional diesel operation.

In addition to that there is a decrease in specific energy consumption at higher loads. Approximately, complete gaseous fuel utilization is realized as a result of the more rapid combustion process and higher temperature. This leads to a reduction of specific energy combustion that is similar to or slightly better than normal diesel operation (Poonia *et al*., 2011). The impact of engine load on specific energy consumption at versus load for normal diesel operation and dual-fuel operation is shown in Fig. 3. Qi *et al*. (2007) discovered that comparable outcomes can be attained by using directly injected LPG-Diesel blends where there is an increase in the fuel consumption of the dual-fuel operation at low loads in comparison to the diesel operation, since the

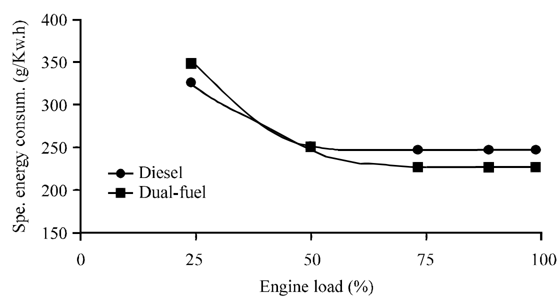

Fig. 3: Specific energy consumption (g/kWh) vs. load (PFI LPG-diesel)

combustion is delayed into the expansion stroke because of the reduced cetane number of the blended fuel which prolongs the delay in ignition. On the other hand, at high loads of the LPG content of fuel blend, the fuel economy increases since the fuel economy is similar to that of the conventional diesel operation. In addition, the brake specific fuel consumption of the engine increased at 20% load making the engine operation more expensive.

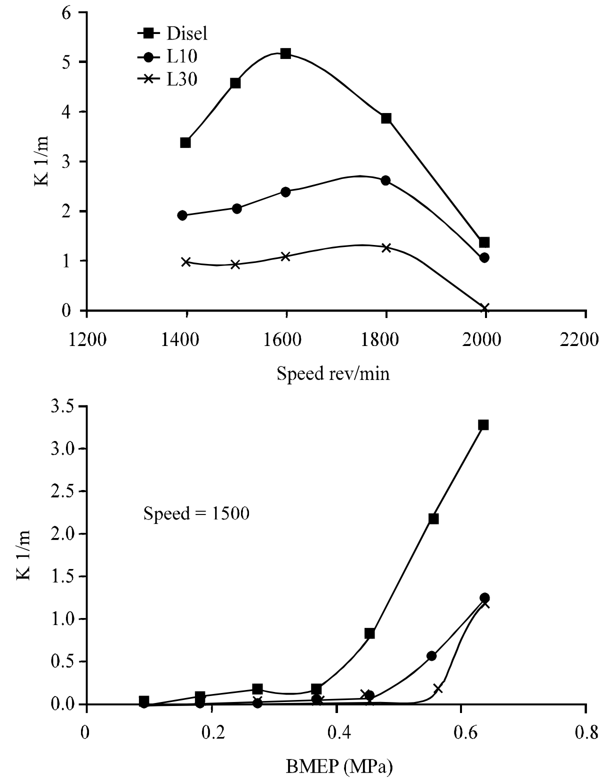

Fig. 4: Smoke emissions of diesel and two different LPG-diesel blends vs. BMEP and engine speed (Donghui and Shenghua, 2005)

On another hand, at 80% load the brake specific fuel consumption reduced with a growth in the LPG content (Rao *et al.*, 2011).

Particular Matter (PM): Particulate Matter (PM) also known as smoke or soot which compression ignition engines emit is mainly generated as a result of the hydrocarbon fuel's incomplete combustion. A mechanism model which was designed for PM was presented by Kayes and Hochgreb (1999) where they named liquid fuel nucleation that stems from the port fuel to inject as the reason for PM formation. Gas-phase nucleation in fuel-rich conditions can also result in the creation of PM. PM is significantly affected by the A/F ratio and likewise, the PM amount in the exhaust gas emissions increases by the burning of the liquid fuel (Kayes and Hochgreb, 1999). The study conducted on the usage of dual fuel engine which is fueled with directly injected LPG-diesel blend reveals that when the LPG-fraction increases, the smoke emission reduces and this is illustrated in Fig. 4-5. In Fig. 4, 10 and 30% LPG content in the fuel blend are represented respectively and the LPG content of the fuel is represented by "z" in Fig. 5. In comparison to normal

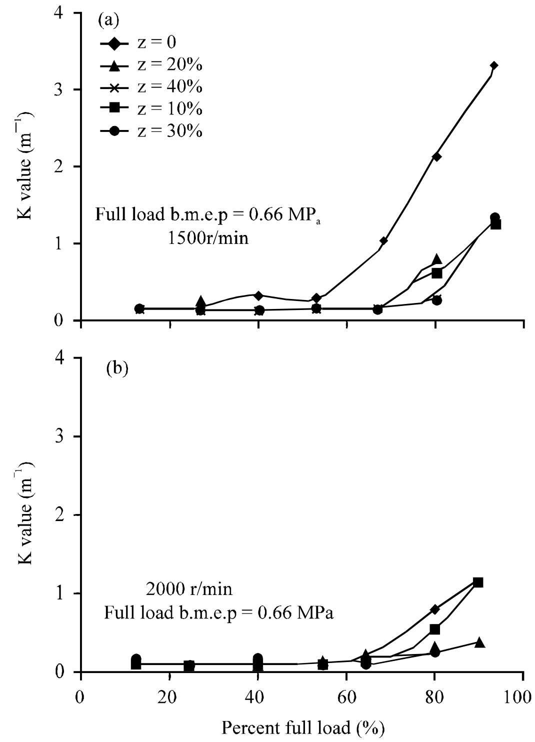

Fig. 5: Smoke emissions for different fuel blends and engine speed vs. load (Qi *et al.*, 2007)

diesel operation, the most notable decrease of particulate matter emission occurs at high loads (≥70%). LPG evaporates with greater ease because of its lower boiling temperature and due to the pressure drop. The injected blend of LPG and diesel-LPG content evaporates immediately, thereby enhancing the spray's gas disturbance. This process is known as "flash boiling" and smaller droplets of blended fuel (in comparison to a conventional diesel injection) are formed in the combustion chamber as the result. Less fuel-rich areas and better mixing and therefore lower particulate matter emissions result from the smaller droplets (Donghui and Shenghua, 2005; Qi *et al.*, 2007). In comparing the soot emissions of normal diesel combustion and dual-fuel combustion with different LPG/diesel ratios, a reduction in soot emission can be found with an increase of the LPG content. Nearly 70% soot emission reduction is realized in a specific case where 42% LPG is added. Moreover, it has been mentioned that soot emissions will not be significantly improved with a further increase in the amount of LPG content.

Nitrogen Oxides (NO_x): The majority of the Nitrogen Oxides (NO_x) which is created in coal combustion is Nitric

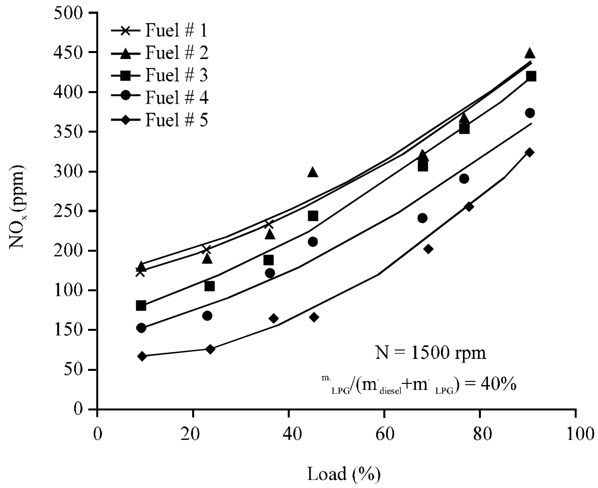

Fig. 6: Variation NO_x of concentration with engine load for LPG blends (Saleh, 2008)

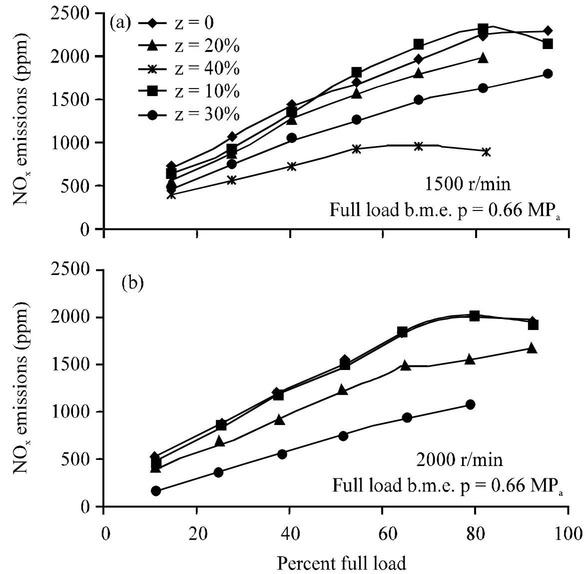

Fig. 7: Variation of nitrogen oxide under diesel and blended fuels operation vs. load at 1500 and 2000 r/min engine speed (Qi *et al*., 2007)

Oxide (NO) and Nitrogen dioxide (NO_2) commonly named in combination as (NO_x). NO_x created during the combustion mainly consists of NO (90-95%) along with lesser amounts of NO_2 (5%-10%). Moreover, the amount of formed (N_2O) is significantly low. For coal and coal-derived fuels, the fuel-bound NO_x mechanism is normally used where nitrogen in considered to be chemically bound to the main fuel. The NO_x formation depends on a number of nitrogen compounds that exist in the fuel-air mixture, stoichiometric conditions and the local combustion's temperature.

However, the NO_2 mechanism is basically established by calculating the chemical kinetic energy near the flame zone where NO_2 is formed due to the actions of HO_2 and NO. After that, NO_2 will react with O and H radicals for the formation of NO_x. In a similar manner, the N_2O mechanism is based on calculating the chemical kinetic energy where the N_2O formation happens due to the action of various nitrogen radicals with (NO_x). Lastly, the formation of NO_x occurs as a result of N_2O's reaction with oxygen radicals. In short, the NO_x formation has yet to be examined and it cannot be claimed that the entire related routes have been found (Hairuddin *et al*., 2014; Kuo, 2005).

Normally, most parts of the NO_x formation are determined through the peak temperature in the combustion process were the peak temperature relies on other parameters such as the initial temperature of the fuel-air mixture, equivalence ratio and the fuel composition (Kuo, 2005). In addition, the highest in-cylinder temperatures of over 1800K create more NO_x resulting from higher equivalence ratio (Hairuddin *et al*., 2014). Saleh (2008) conduct the effect of different LPG blends on NO_x emissions in comparison with pure propane in dual fuel operation is illustrated in Fig. 6. The emission of NO_x increased for the entire LPG blends with an increase in the engine load. On the other hand, the increase in the percentage of butane is shown to correspond with NO_x emission reduction. NO_x with 10, 30, 50 and 70% butane was lower by almost 1, 6.7, 16.7 and 27.8%, respectively at full load than that with pure propane. Generally, high NO_x levels are formed as a result of high temperatures and high oxygen amounts; conditions which do not occur in the combustion chamber with enhancing the percentage of butane.

Additionally, Qi *et al*. (2007) conduced an experimental by using diesel-LPG dual fuel engine and compared with normal diesel engine at different engine speed (1500, 2000 rpm) and the result show that the NO_x concentration decreased with increased the LPG concentration in diesel fuel and that because of increase the heat of evaporation of the diesel-LPG blended and as a result decrease the temperature of the cylinder gases due to the fuel evaporation. As well, the increase of engine speed under blended fuel operation results in a further decrease of NO_x values compared to Diesel fuel operation as illustrate in Fig. 7.

Unburned hydrocarbons: Unburned Hydrocarbon (UHC) is a consequence of incomplete combustion caused by slow temperatures (Bression *et al*., 2008; Ganesh *et al*., 2008; Yap *et al*., 2006) during the combustion process which results in fuel deposition in crevices and boundary layers (Hairuddin *et al*., 2014). UHC is originated from the cylinder wall which maintains a thin layer of oil as the

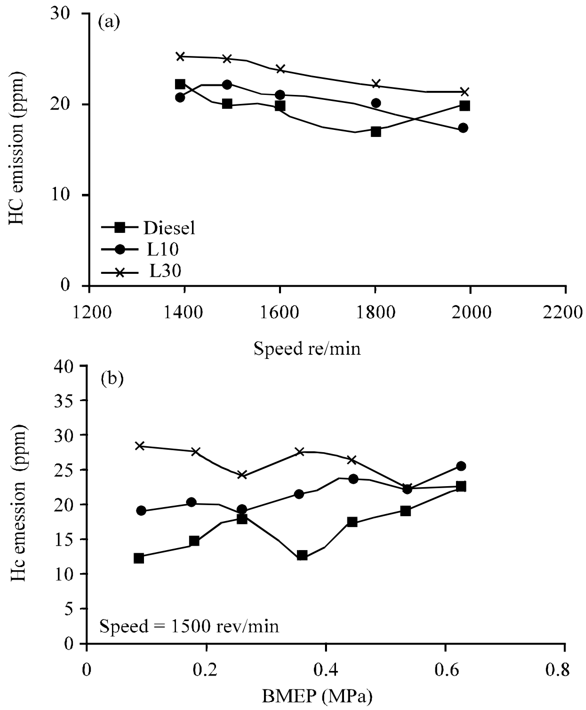

Fig. 8: HC emissions (ppm) vs. engine speed and loads for different diesel/LPG blends and net diesel (Donghui and Shenghua, 2005)

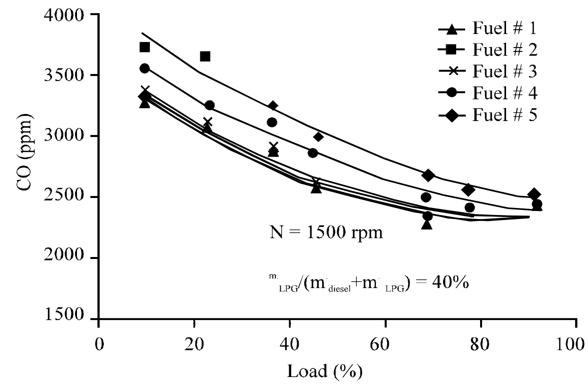

Fig. 9: Variation of CO concentration with engine load for LPG blends (Saleh, 2008)

piston is going down that accumulates and amasses in the crevice area and any other cold region of the combustion wall (Heywood, 1988; Komninos, 2009). Donghui and Shenghua (2005), investigated and observed various LPG/diesel ratios which are shown in Fig. 8. They found that UHC has the tendency to increase when it runs on LPG DI, PFI and diesel in dual-fuel mode. However, operating under low loads and high ratios of LPG/diesel leads to increased UHC emissions because of the crevices mechanisms and the lower charge temperature. While direct injection of an LPG/diesel mixture positively impacts the CO emissions such impact is not observed on UHC emissions. Moreover, greater levels of UHC will be emitted when the LPG/diesel ratio is enhanced at high loads probably because of higher temperatures that result in a more thorough combustion of the air-fuel blend (Donghui and Shenghua, 2005; Qi *et al*., 2007).

Carbon monoxide (CO): The emission of CO is normally controlled by the fuel-air equivalence ratio to a large extent (Heywood, 1988; Stone, 1999). The most important mechanism of CO formation is RH-R-RO_2-RCHO-RCO-CO where R represents the hydrocarbon radical (Heywood, 1988). The oxidation of CO is d ominated by the reaction of carbon monoxide and OH radical as CO+OH = CO_2+H, the outcome of which also includes hydrogen radicals. In a similar way, the CO to CO_2 conversion happens with an increase in the OH radicals' concentration during the process of combustion (Kuo, 2005). The combustion's low temperature eventually results in the decrease of the combustion efficiency due to lower oxidation activities of hydrocarbons and the lower rate of conversion of CO to CO_2 (Sjoberg and Dec, 2005). CO emissions originate from significantly cold boundary and crevices layers where complete consumption is not possible (due to the coldness) (Hairuddin *et al*., 2014). The impact of different LPG mixtures on the mission of CO under various loadings related to the pure propane was observed by Saleh (2008) in the dual-fuel operation which is illustrated in Fig. 9. As expected, the 30, 50 and 70% increase of the butane in the LPG composition resulted in the highest CO emissions. Therefore, with an increase in the percentage of the butane, the CO emissions were expected to increase in comparison to pure propane gas because of its lower flame speeds and flame temperature, longer ignition delays and higher C/H ratios (Saleh, 2008). Moreover, there is a significant difference between the CO emission of a dual-fuel operation with direct injection of LPG-diesel mixture and a normal dual-fuel operation gaseous fuel is port injected. This is illustrated in Fig. 10 in which a comparison between diesel and mixtures that contain 10 and 30% LPG is conducted. A small increase in CO emission is noticed at low loads which enhance with an increase in the quantity of LPG because of the low charge temperature. However, at high loads, there is a decrease in CO emission when the LPG amount increases; this reduction in CO emission is significant compared to the levels in normal diesel operation. Due to LPG's flash-boiling in the mixture, the fuel mixture mixes better with the air and moreover, higher temperatures will result

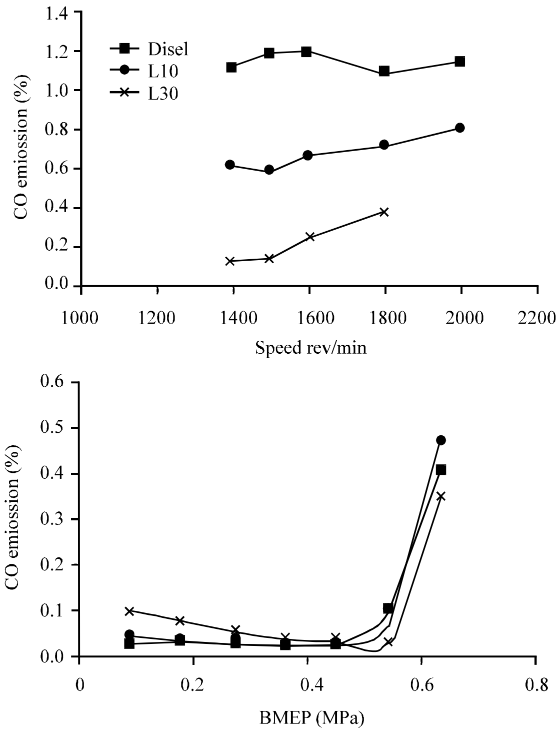

Fig. 10: CO emissions (ppm) vs. engine speed and loads for different diesel/LPG blends and net diesel (Donghui and Shenghua, 2005)

from high loads. Therefore, the complete combustion is attained. The CO emission formation does not appear to be significantly affected by the engine speed (Donghui and Shenghu, 2005; Qi *et al*., 2007).

RESULTS AND DISCUSSION

Effect of addition hydrogen along with lpg as a primary gaseous fuel and diesel as pilot fuel: A study on a 4-cylinder diesel engine in a dual-fuel mode with diesel as the pilot fuel and the addition of H_2 and LPG as the primary gaseous fuel has been carried out by Lata *et al*. (2011, 2012), Lata and Misra (2010, 2011). To determine the emission, combustion and performance characteristics. It was found in this study that the mixture combination of LPG-hydrogen ratio (70:30) increased the brake thermal efficiency as compared to diesel Cases at 80% load conditions as shown in Fig. 11. Since, LPG flame has the tendency of becoming unstable whereas hydrogen-air flame has the tendency of becoming stable. Therefore, hydrogen fraction results in flame stabilization.

Figure 12a and b illustrates the variation of UHC at load conditions of 10 and 80%. The UHC emissions

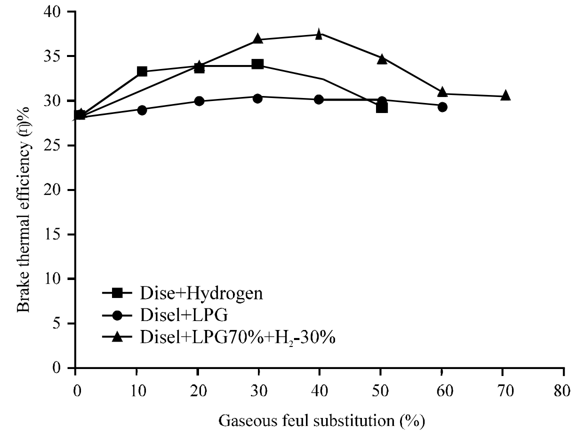

Fig. 11: Comparison of brake thermal efficiency for the cases 2-4 at 80% load condition (Lata *et al*., 2012)

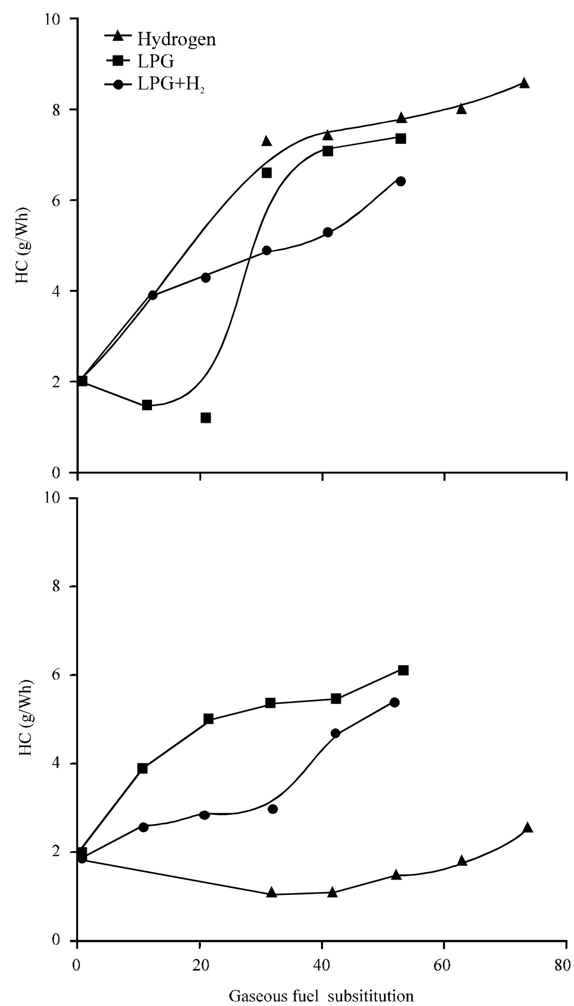

Fig. 12: Unburnt HC (g/kWh) vs. diesel+gaseous fuels substitution (%) (Lata *et al*., 2012)

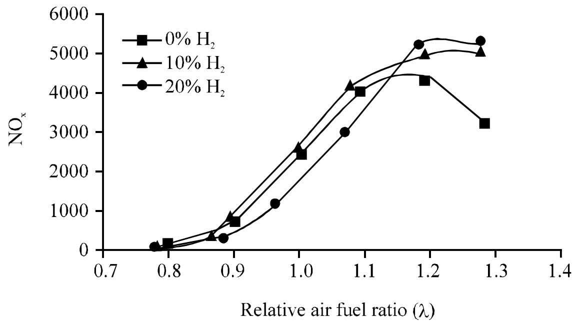

Fig. 13: Variation of emissions with relative air-fuel ratio

increased when LPG-hydrogen at 10% low load compared with diesel mode and this might be because of the decrease in the amount of pilot fuel which is the cause of the gaseous fuel's poor ignition and moreover, the inducted mixture is too lean to burn. On the other hand, a lower UHC emission can observe in LPG-Hydrogen in 80% high load as compared to diesel mode since the faster and better combustion rate which results in a complete combustion, thereby, lower UHC emissions.

Moreover, a comparison between hydrogen and LPG was carried out by Choi *et al.* (2005). Different hydrogen amounts (0, 10 and 20%) at 1400 rpm were used to examine the impact of NO_x emission which is illustrated in Fig. 13. NO_x emissions were reported to be the highest at addition of 20% hydrogen results in an almost 20% increase in the NO_x emission amount and this is in comparison with pure LPG combustion since higher NO_x emissions resulting from the addition of hydrogen, depend on the flame temperature of the hydrogen fuel and the maximum temperature of the cylinder (which are higher in comparison to LPG combustion). However, due to the 10% addition of hydrogen, the NO_x emission amounts will be high in comparison to the pure LPG fuel.

CONCLUSION

Experiments and research conducted by different scientists revealed that the employment of LPG in the diesel engine as the dual-fuel operation is among the effective and prominent measures of overcoming fossil fuel exhaust emissions and scarcity. The LPG diesel dual-fuel engine's emission, combustion and performance characteristics have been examined in different experimental studies. The below conclusions are made based on the present study on an LPG-diesel dual fuel engine: LPG-diesel dual fuel engines have issues like poor brake thermal efficiency at low load; the brake thermal efficiency increases at higher load conditions. Generally, there is a slight increase in the specific energy consumption in diesel dual fuel operation at low loads and yet, the specific energy consumption decreases at higher loads since the gaseous fuel is almost completely utilized because of faster proceeding combustion and higher temperatures. The most significant PM emission reduction in comparison to normal diesel operation is observed at high loads. This because the process is known as "flash boiling" and leads to smaller droplets of blended fuel in the combustion chamber in comparison to a conventional diesel injection. The smaller droplets lead to better mixing and as a result, reduction in particulate matter emissions. NO emissions increased in the highest in-cylinder temperatures of over 1800 K. However, the increase in the percentage of butane is shown to correspond with NO_x emission reduction compared with pure propane. The majority of carbon monoxide and unburned hydrocarbon emissions are due to incomplete combustion. Unburned fuel in crevices volumes is one of the main sources of gaseous fuel's incomplete combustion and poor flame propagation. However, the carbon monoxide emission reduces in direct injected LPG-diesel mixtures. The brake thermal efficiency will be enhanced at high loads with the utilization of LPG and hydrogen as secondary fuel whereas reverse effects are produced as low conditions. At higher load conditions, NO_x and unburnt hydrocarbon will decrease with the use of an LPG and hydrogen mixture as secondary fuel

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REFERENCES

Agarwal, A.K., 2007. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Prog. Energy Combust. Sci., 33: 233-271.

Amarendar, R.G., R.C.V. Mohan and R.K. Govinda, 2008. Experimental investigation of a single-cylinder, four-stroke diesel engine operating on the dual-fuel mode (LPG+ Diesel). Intl. J. Sci. Comput., 2: 145-152.

Balat, M., 2008. Potential importance of hydrogen as a future solution to environmental and transportation problems. Int. J. Hydrogen Energy, 33: 4013-4029.

Bora, B.J., B.K. Debnath, N. Gupta, N. Sahoo and U.K. Saha, 2013. Investigation on the flow behaviour of a venturi type gas mixer designed for dual fuel diesel engines. Int. J. Emerging Technol. Adv. Eng., 3: 202-209.

Bression, G., D. Soleri, S. Savy, S. Dehoux and D. Azoulay *et al*., 2008. A study of methods to lower HC and CO emissions in diesel HCCI. SAE. Int. J. Fuels Lubr., 1: 37-49.

Choi, G.H., Y.J. Chung and S.B. Han, 2005. Performance and emissions characteristics of a hydrogen enriched LPG internal combustion engine at 1400rpm. Int. J. Hydrogen Energy, 30: 77-82.

Donghui, Q. and Z.L. Shenghua, 2005. Experimental studies on the combustion characteristics and performance of a naturally aspirated, direct injection engine fuelled with a liquid petroleum gas diesel blend. J. Automobile Eng., 219: 253-261.

Elnajjar, E., M.O. Hamdan and M.Y.E. Selim, 2013a. Experimental investigation of dual engine performance using variable LPG composition fuel. Renewable Energy, 56: 110-116.

Elnajjar, E., M.Y. Selim and M.O. Hamdan, 2013b. Experimental study of dual fuel engine performance using variable LPG composition and engine parameters. Energy Convers. Manage., 76: 32-42.

Ergenc, A.T. and D.O. Koca, 2014. PLC controlled single cylinder diesel-LPG engine. Fuel, 130: 273-278.

Ganesh, D., G. Nagarajan and M.M. Ibrahim, 2008. Study of performance, combustion and emission characteristics of diesel homogeneous charge compression ignition (HCCI) combustion with external mixture formation. Fuel, 87: 3497-3503.

Goldsworthy, L., 2012. Combustion behaviour of a heavy duty common rail marine diesel engine fumigated with propane. Exp. Therm. Fluid Sci., 42: 93-106.

Hairuddin, A.A., T. Yusaf and A.P. Wandel, 2014. A review of hydrogen and natural gas addition in diesel HCCI engines. Renewable Sustainable Energy Rev., 32: 739-761.

Heywood, J., 1988. Internal Combustion Engine Fundamentals. McGraw-Hill Education, New York, USA.,.

Kayes, D. and S. Hochgreb, 1999. Mechanisms of particulate matter formation in spark-ignition engines. 1: Effect of engine operating conditions. Environ. Sci. Technol., 33: 3957-3967.

Komninos, N.P., 2009. Investigating the importance of mass transfer on the formation of HCCI engine emissions using a multi-zone model. Appl. Energy, 86: 1335-1343.

Kuo, K.K., 2005. Principles of Combustion. 2nd Edn., John Wiley and Sons, New York.

Lata, D.B. and A. Misra, 2010. Theoretical and experimental investigations on the performance of dual fuel diesel engine with hydrogen and LPG as secondary fuels. Int. J. Hydrogen Energy, 35: 11918-11931.

Lata, D.B. and A. Misra, 2011. Analysis of ignition delay period of a dual fuel diesel engine with hydrogen and LPG as secondary fuels. Int. J. Hydrogen Energy, 36: 3746-3756.

Lata, D.B., A. Misra and S. Medhekar, 2011. Investigations on the combustion parameters of a dual fuel diesel engine with hydrogen and LPG as secondary fuels. Int. J. Hydrogen Energy, 36: 13808-13819.

Lata, D.B., A. Misra and S. Medhekar, 2012. Effect of hydrogen and LPG addition on the efficiency and emissions of a dual fuel diesel engine. Int. J. Hydrogen Energy, 37: 6084-6096.

Lee, J., S. Choi, H. Kim, D. Kim and H. Choi *et al*., 2013. Reduction of emissions with propane addition to a diesel engine. Int. J. Automot. Technol., 14: 551-558.

Leermakers, C.A.J., V.D.B. Berge, C.C.M. Luijten, D.L.P.H. Goey and S. Jaasma, 2011. Direct injection of diesel-butane blends in a heavy duty engine. SAE. Int. J. Fuels Lubr., 4: 179-187.

Murthy, K., N. Madhwesh and B.R. ShrinivasaRao, 2012. Influence of injection timing on the performance of dual fuel compression ignition engine with exhaust gas recirculation. Int. J. Eng. Res. Dev., 1: 36-42.

Paykani, A., R.K. Saray, A.M. Kousha and M.S. Tabar, 2011. Performance and emission characteristics of dual fuel engines at part loads using simultaneous effect of exhaust gas recirculation and pre-heating of in-let air. Int. J. Automot. Eng., 1: 53-53.

Pirouzpanah V. and K.R. Saray, 2007. Comparison of thermal and radical effects of EGR gases on combustion process in dual fuel engines at part loads. Energy Convers. Manage., 48: 1909-1918.

Poonia, M.P., A. Bhardwaj, A.S. Jethoo and U. Pandel, 2011. Experimental investigations on engine performance and exhaust emissions in an LPG diesel dual fuel engine. Int. J. Environ. Sci. Dev., 2: 418-418.

Qi, D.H., Y.Z. Bian, Z.Y. Ma, C.H. Zhang and S.Q. Liu, 2007. Combustion and exhaust emission characteristics of a compression ignition engine using liquefied petroleum gas diesel blended fuel. Energy Convers. Manage., 48: 500-509.

Rao, G.A., A.V.S. Raju, C.V.M. Rao and K.G. Rajulu, 2011. Effect of LPG content on the performance and emissions of a diesel LPG dual fuel engine. Bangladesh J. Sci. Ind. Res., 46: 195-200.

Rao, G.A., A.V.S. Raju, K.G. Rajulu and C.M. Rao, 2010. Performance evaluation of a dual fuel engine (Diesel+ LPG). Indian J. Sci. Technol., 3: 235-237.

Raslavicius, L., A. Kersys, S. Mockus, N. Kersiene and M. Starevicius, 2014. Liquefied petroleum gas (LPG) as a medium-term option in the transition to sustainable fuels and transport. Renewable Sustainable Energy Rev., 32: 513-525.

Saleh, H.E., 2008. Effect of variation in LPG composition on emissions and performance in a dual fuel diesel engine. Fuel, 87: 3031-3039.

Sjoberg, M. and J.E. Dec, 2005. An investigation into lowest acceptable combustion temperatures for hydrocarbon fuels in HCCI engines. Proc. Combust. Inst., 30: 2719-2726.

Stewart, J., A. Clarke and R. Chen, 2007. An experimental study of the dual-fuel performance of a small compression ignition diesel engine operating with three gaseous fuels. J. Automobile Eng., 221: 943-956.

Stone, R., 1999. Solutions Manual for Introduction to Internal Combustion Engines. Macmillan Education, London, UK., ISBN:978-0-333-79307-7.

Yamik, H., 2002. Investigation of the Possibility of Using Oil Esters as Alternative Fuel in Diesel Engines. Gazi University, Ankara, Turkey,.

Yap, D., S.M. Peucheret, A. Megaritis, M.L. Wyszynski and H. Xu, 2006. Natural gas HCCI engine operation with exhaust gas fuel reforming. Int. J. Hydrogen Energy, 31: 587-595.