

Performance and Exhaust Analysis of Direct Injection Diesel Engine Running on Dual Fuel

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Abstract

The propane (LPG) is one of the best candidates for an alternative fuel in dual fuel engines which operate primarily on any type of gaseous fuel using pilot injection of diesel to achieve ignition. An experimental investigation of the effect of LPG /diesel blend Fuel on emissions and performance in a dual fuel diesel engine is presented to obtain the best mass ratio of substitution of the diesel fuel with maintaining high thermal efficiency comparable to a conventional engine. The direct injection diesel engine was converted to pilot-injected dual fuel operation to operate under LPG /diesel blend Fuel for a range of load variations. From the results, it is shown that, The test engine ran smoothly and satisfactorily up to 90% of diesel fuel substitution and the ratio of $m_{\text{propane}} / (m_{\text{diesel}} + m_{\text{propane}}) = 40\%$ substitution of the diesel fuel is the best for maintaining the high thermal efficiency comparable to a conventional engine. At part loads, tests were made by using the Exhaust Gas Recirculation (EGR) method to improve the engine performances and exhaust emissions. A better trade-off between CO and NO_x emissions for fuel #2 can be attained within a limited EGR rate of 5% ~ 15% at part loads.

1. Introduction

Diesel engines have considerable advantages in the aspect of engine power, durability, fuel economy and very low CO emissions. They are widely applied in vehicles from small to large. However, the exhaust emission from diesel engines is still a serious problem, and an international concern has been risen for its control and restriction. Hence, in order to meet the environmental legislations, it is highly desirable to reduce the amount of NO_x in the exhaust gas. Therefore, energy conservation with high efficiency and low emission are important research topics for development of engine system. Recently, the diesel engine which uses alternative fuels such as natural gas (CNG, LNG), LPG (Liquefied Petroleum Gas), DME (Dimethyl Ether), and hydrogen is actively developed to solve these problems [1].

Some investigations have been dedicated to the investigation of the feasibility of using gaseous fuels as alternative engine fuels from both performance and emissions perspectives. Many of the results reported so far have concentrated on the use of natural gas as the alternate fuel for internal combustion engines [2]. The effect of injection timing of pilot fuel and pilot fuel quantity on the performance and emissions of an indirect Diesel engine fueled with methane or propane is found by [3, 4]. It is shown that the low efficiency and poor emissions at light loads can be improved significantly by advancing the injection timing of the pilot fuel or increasing the amount of pilot fuel, while increasing the amount of pilot fuel at high loads led to early knocking. The cycle-to-cycle combustion variation as reflected in the combustion pressure data of a single cylinder, naturally aspirated, Ricardo E6 engine converted to run as dual fuel engine on diesel and gaseous fuel of LPG or methane have been studied under various combination of engine operating and design parameters [5]. Pirouzpanahis [6] investigated the combustion characteristics of a dual fuel (Diesel–gas) engine at part loads using a single zone combustion model with detailed chemical kinetics for combustion of natural gas fuel. The combustion model is able to establish the development of the combustion process with time and the associated important operating parameters, such as pressure, temperature, heat release rate (HRR) and species concentration. It is an attempt to investigate the combustion phenomenon at part load and using exhaust gas recirculation. It is found that all the different cases of EGR have positive effects on the

performance and emission parameters of dual fuel engines at part loads despite the negative effect of some diluent gases in the chemical case, which moderates too much the positive effects of the thermal and radical cases of EGR. Also, [7] Cheikhto investigated the emission and performance characteristics of a commercial diesel engine (Deutz FL8 413F) being operated on natural gas with pilot diesel ignition. A computer program has been developed to model the experimental data using a chemical kinetic reaction mechanism of the dual-fuel combustion.

Also, liquified petroleum gas (LPG) is paid to attention as a useful alternative. LPG is thought to be a major energy resource of the future due to its clean burning nature and eventual availability from renewable sources. LPG is widely regarded as a promising transportation fuel because it is clean and renewable [8]. In addition, as LPG is excellent in the exhaust emission and performance, LPG vehicles are being rapidly developed as an economical and low pollution car. There is a much of published research on the use of mixtures of LPG and some of new fuels in diesel and spark-ignition engines. Zhili [9] showed that the diesel engine can run over a wide range of load with a high efficiency and NO_x emissions can be reduced to near zero level if an appropriate proportion of Dimethyl Ether is added with the LPG In order to control the ignition and combustion. Miller [10] has been performed the utilization of LPG as a primary fuel with diethyl ether (DEE) as an ignition enhancer in a direct injection diesel engine to study the performance, combustion and emissions characteristics. it is observed that, the brake thermal efficiency is lowed at full load with a reduction of about 65% NO emission than the diesel operation. The maximum reduction in smoke and particulate emissions is observed to be about 85% and 89%, respectively, when compared to that of diesel operation; however an increase in CO and HC emissions was observed. Also, homogeneous charge compression ignition of LPG and gasoline using variable valve timing with added the Dimethyl Ether in an engine had been studied by [11]. Gyeong [12] studied the effects of hydrogen enriched LPG fueled engine on exhaust emission, thermal efficiency and performance with spark timing was set to minimum spark advance for best torque. Kihyung [13] were investigated the flame propagation and combustion characteristics of LPG using a constant volume combustion chamber To clarify the combustion process of the heavy duty LPG engine. It is found that, the flame propagation reached a maximum speed at the stoichiometric equivalence ratio, regardless of operating conditions and the coefficient of variation of combustion duration increased when the equivalence ratio decreased.

As mentioned above, at present the main interest for gaseous fuels lies with LPG and NG in liquid or gas form, with a large number of small vehicles running in many countries, primarily in Turkey, Italy, Netherland and Japan [14]. The purposes of this paper are as follows. The first is to analyze dual-fuel operation with various proportions of pure propane gas (Fuel #1) as baseline condition and diesel fuel in terms of engine performance and emissions to obtain the best mass ratio of substitution of the diesel fuel with maintaining high thermal efficiency comparable to a conventional engine. The second purpose is to improve the engine performance and emissions for dual fuel mode at low loads by using the exhaust gas recirculation (EGR) method when operating with the fuel #2 (70% propane, 30% butane). The tests and data collection were performed under various conditions of load at engine speed of 1500 rpm

2. Test fuels composition

LPG is the abbreviation of Liquefied Petroleum Gas. This group of products includes saturated Hydrocarbons, Propane (C_3H_8) and Butane (C_4H_{10}), which can be stored separately or as a mixture. They exist as gases at normal room temperature and atmospheric pressure. LPG comes from two sources. It can be obtained from the refining of crude oil. When produced this way it is generally in pressurized form. LPG is also extracted from natural gas or crude oil streams coming from underground reservoirs. 60% of LPG in the world today is produced this way whereas 40% of LPG is extracted from refining of crude oil. The standard of LPG is not universally observed. Because, the concentration of propane as high as virtually 100 %, to as low as 50 % in certain locations. The utilization of LPG as an automotive fuel varies very widely from one country to another, depending on the cost and availability of the fuel in relation to alternative fuels, notably petrol and

diesel [15]. While the term LPG means broadly a mixture of propane and butane. Butane and propane are different chemical compounds; their properties are similar enough to be useful in mixtures. Butane and Propane are both saturated hydrocarbons.

Tested LPG fuel composition used in this study has been described in table 2. These blending fuels were used in this investigation, have been selected as actual study for existing LPG blends as an automotive fuel. Properties of propane, butane and diesel fuel examined in this study are listed in table 3.

Table 2 List of tested LPG fuels composition (% vol.)

Tested fuel	Propane	Butane
Fuel #1	100	-
Fuel #2	70	30

Table 3 Fuels properties

Property	Propane	Butane	Diesel
Specific gravity, for gas at (15 ⁰ C, 1 atm) for Diesel fuel at 15 ⁰ C	1.55 gas	2.07 gas	0.83 liquid
Calorific value, kJ/kg	46300	45800	43162
Sulphur content by weight, %	0.02	0.02	0.5
Theoretical air requirement, kg/kg	15.6	15.4	14.5
Flame temperature, ⁰ C	1980	1775	1720
Boiling point, ⁰ C	-42	-0.5	260
Lower flammability limit, vol %	2.1	1.86	0.6
Upper flammability limit, vol %	10.1	8.41	5.6

3. Experimental equipment

In this section, the overall experimental setup used to investigate the performance and emissions characteristics of diesel engine and dual fuel combustion is briefly described. In the dual-fuel engines, a charge of mixture of gaseous fuel and air is compressed rapidly to high temperatures and pressures, then ignited by the injection of a small quantity of diesel fuel just before the end of compression stroke [16]. The major advantage of this system is the ability to burn very lean air-fuel mixtures with high efficiency. This is due to the reliable, high energy ignition source provided by the pilot fuel, and to the rapid combustion of the gas/air charge. In this study, existing diesel engines fairly readily be converted from a direct injection combustion mode to the dual-fuel mode of combustion. Hence, the LPG blends was inducted into the cylinder of a diesel engine from an intake manifold and ignited with light oil that is injected into the engine cylinder. For reference, the ordinary diesel condition that only air is inducted into the cylinder was also performed.

The experiments were carried out on a two-cylinder, water cooled, four-stroke, Diesel engine with a direct injection type of combustion chamber. It was necessary to make some of modifications in the engine since the original engine was not prepared for dual-fuel system and had not EGR. The first modification was the propane and butane gas (LPG blends) was introduced through orifice plate, a needle valve and a gas mixer to the engine inlet manifold where the gas fuel mixes with the incoming airflow through multi-point injection. The second one was the exhaust manifold was connected with the air intake manifold through exhaust gas recirculation (EGR) valve. Here as well, the EGR used to investigate the effect of EGR

on emissions and engine performance at part loads performance in a dual fuel diesel engine. The experimental set up is shown schematically in Fig.1 and comprises a hydraulic dynamometer, a pressure tank, a diesel particulate bag filter, a heat exchanger, an EGR valve, a liquid and gas fuel metering systems, and an exhaust gases analysis system. The basic engine characteristics of the test engine are summarized in table 4. It was necessary to connect the exhaust manifold with the air intake manifold, with a pressure tank, bag filter, a heat exchanger and an EGR valve at this connection. The bag filter is used for particulate reduction and supply of clean gas for EGR. The pressure tank is used for reduction of exhaust pressure pulse and the heat exchanger is used as an exhaust cooler for cooling exhaust gas by water flow. This allowed for EGR temperatures to not only be controlled but also lowered to temperatures that are not achievable in a normal engine setup. An EGR valve was installed in this connection that enabled manual to control the flow rate of EGR to the intake manifold to attain various EGR ratios. The EGR mass rate is the ratio between recirculated exhaust mass flow and the total mass flow allowed to pass into the engine.

$$\text{EGR rate (\%)} = \left(\frac{m_{\text{EGR}}}{m_{\text{Air}} + m_{\text{Fuel}}} \right) \times 100$$

The engine was coupled to a water brake dynamometer to provide the required torque absorption. The dynamometer torque was measured using an inductive torque transducer operating on the basis of a transformer having a variable coupling factor. This transducer was used in conjunction with a signal processing module that allows the torque and speed values to be displayed digitally

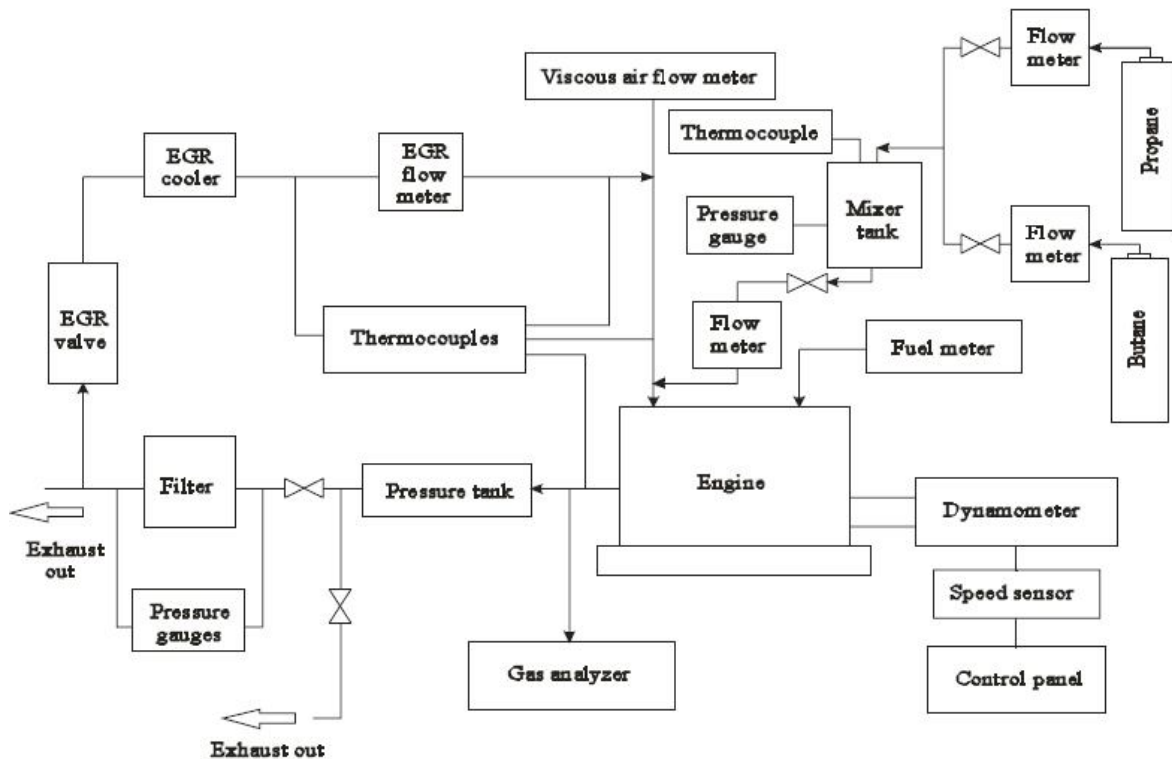


Fig. 1 Schematic of the experimental test rig

Table 4 Test engine specifications

MODEL	112M- Helwan
Type	4-stroke direct injection
Cooling	Water cooling

Number of cylinder	2
Diameters of cylinder (mm)	112
Stroke length (mm)	115
Capacity (cm ³)	2266
Compression ratio	16.4
Rated speed (rpm)	1500
Rated power (HP)	26

The flow rate of air into the engine was measured using a laminar flow element (LFE). The laminar flow element was a honeycomb-like structure, which provides for a certain pressure drop across itself for a certain volumetric flow rate of air. This pressure drop was measured using an inclined manometer. Volumetric flow rate of air was then calculated based on the measured pressure drop and the correspondence between pressure drop and volumetric flow rate obtained from the LFE calibration. The flow rate of EGR into the engine was measured with a sharp edge orifice mounted on a pipe connected to the pressure tank. Also, propane and butane flow rates were determined by calibrated a sharp edge orifice mounted on a pipe attached to a gas mixer tank. An inclined manometer was used to measure the pressure drop across the orifice. The fuel consumption is measured by a fuel meter. The air temperature, exhaust gas temperature were measured using type K thermocouples and the CO, SO_x and NO_x levels were obtained with a gas analyzer lancom 6500 was used to measure engine exhaust pollutant emissions. Pressure gauges were fitted to measure the pressure of EGR, inlet mixer and fresh intake air. A full set of readings was taken for each data point recorded thus the EGR rate can be calculated based on the above data.

4. RESULTS AND DISCUSSION

The experimental results are given in three sections. The first section compares dual-fuel operation with various proportions of pure propane gas (Fuel #1) as baseline condition and diesel fuel in terms of engine performance and emissions to obtain the best ratio of $m_{\text{propane}} / (m_{\text{diesel}} + m_{\text{propane}})$ substitution of the diesel fuel with maintaining high thermal efficiency comparable to a conventional engine. The second section introduces improving of the engine performance and emissions for dual fuel mode at two low loads (10%, 25% of full load) by using the exhaust gas recirculation (EGR) when operating with Fuel #2. The EGR rate, as mass of exhaust gases recycled divided by total inlet charge is varied from 0% (no EGR) to 20%. The tests and data collection were performed under various conditions of load (10%, 25%, 40%, 50%, 75%, 85%, 100% of full load) and at engine speed of 1500 rpm.

4.1 Comparison of performance and emissions with dual and diesel fuel

4.1.1 Engine performance

As mentioned above, for dual fuel operation the propane is aspirated with the incoming air to the cylinder, so the combustion occurs partially in pre-mixed mode. The diesel pilot flame acts as an ignition source for the propane/air mixture. The effect of energy substituted by pure propane (Tested fuel #1) was varied from 0% (conventional diesel engine) to 90% for various engine loads at 1500 rpm with energy conversion efficiency is shown in Fig.2. The results show that a slight increase in the thermal conversion efficiency than of normal diesel engine at different engine loads with increasing the propane up to 40 %. The thermal conversion efficiency decreases than of normal diesel engine with increase the percent of gaseous fuel up to 90%. The main reason of decreasing the thermal conversion efficiency is the increase of the ignition delay period with increasing the percent of propane and also, the flame propagation in gas-air mixture is much slower at higher

percent gas and the lower pilot fuel quantities. It would be noticed that the substitution of 40% of the diesel fuel does not affect significantly the engine performance as obviously in Fig. 3 at over all load conditions. So, the ratio of $m_{\text{propane}} / (m_{\text{diesel}} + m_{\text{propane}}) = 40\%$ substitution of the diesel fuel is the best for maintaining the high thermal efficiency comparable to a conventional diesel engine.

The effect of various engine loads on the thermal conversion efficiency and brake specific fuel consumption (bsfc) of dual fuel combustion (40% of pure propane) with comparable to a conventional engine are shown in Fig.3. It will be seen that the efficiency increase with load for both dual fuel operation and diesel engine. At high loads, it is found that the dual fuel operation is efficient than corresponding diesel operation about 2.3% at full load. This trend may be explained by increasing of the heat release as a result of the overall equivalence ratio increases and the combustion tends to be more complete, leading to high cylinder pressures and increased power output. The bsfc at full load is decreased about 4.2% as compared to bsfc value when engine running on pure diesel as shown in Fig. 3. At 25% load the thermal conversion efficiency of dual fuel is lower than diesel operation with 2% since the combustion of the gas fuel occurs at very fuel lean mixtures, burning rate is relatively slower for half load and slowest for quarter load. The incomplete combustion with very slow burning is the main reason for reduced power output and poor fuel conversion efficiency of dual fuel at low loads.

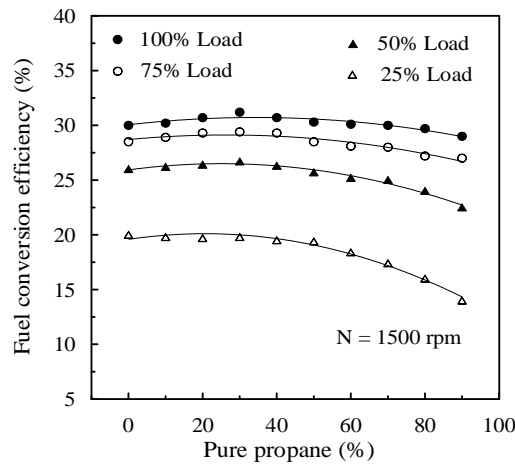


Fig. 2 Fuel conversion efficiency versus percent energy substituted by propane gas

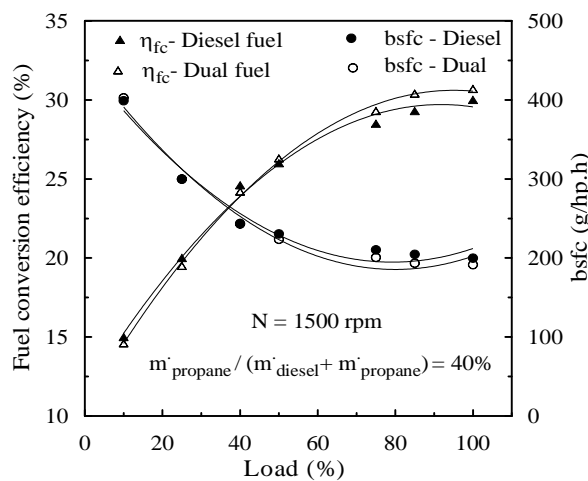


Fig. 3 Fuel conversion efficiency and bsfc as a function of load at N = 1500 rpm

4.1.2 NO_x Emissions

The nitrogenous oxides (NO_x) concentration versus engine load for dual fuel mode (fuel #1) and pure diesel is illustrated in Fig. 4. As the load on the engine was increased, NO_x emissions also increased for both dual fuel operation and diesel engine because of an increase in the cylinder combustion temperature and pressure with load. This is considered to be the main reason for the increase in NO_x emissions through Zeldovich mechanism [17]. It would be expected that the fuels with the highest in-cylinder temperature levels would have the highest NO_x. Since diesel fuel was higher combustion chamber temperature as indicated from measured exhaust gas temperature, as shown in Fig. 5, higher NO_x emissions were observed with diesel fuel engine. At full load NO_x emissions reached a value of 575 ppm for diesel engine operation and 450 ppm for dual fuel operation. At 25% load, the NO_x were 243 ppm and 200 ppm for diesel engine and dual fuel operation respectively. It can be noticed that the difference of NO_x emissions between diesel engine and dual fuel operation is amplified with increase of the engine load however the gas fueling fraction increases in dual fuel operation. The main reason is that the propane acts as a diluent in the unburned mixture, increasing the heat capacity of the cylinder charge and reducing effectively the amount of free oxygen that can react with nitrogen to produce NO_x. As a consequence the temperatures inside the cylinder are lower, as shown in Fig. 5, "freezing" the NO_x formation chemistry.

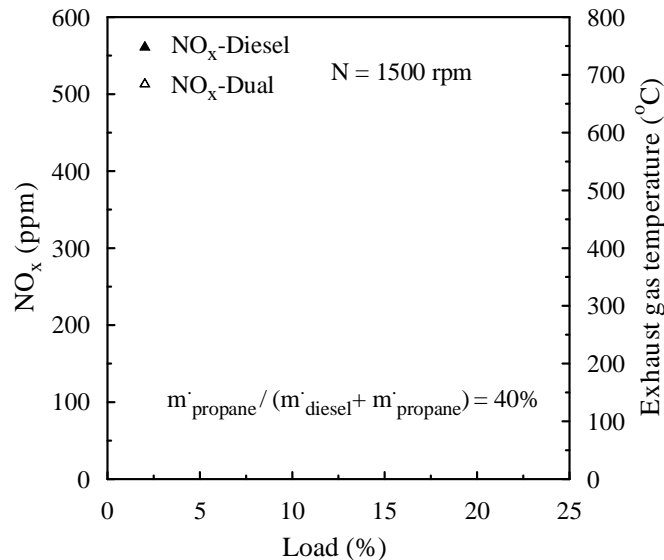


Fig. 4 Variation of NO_x concentration and Egt with engine load

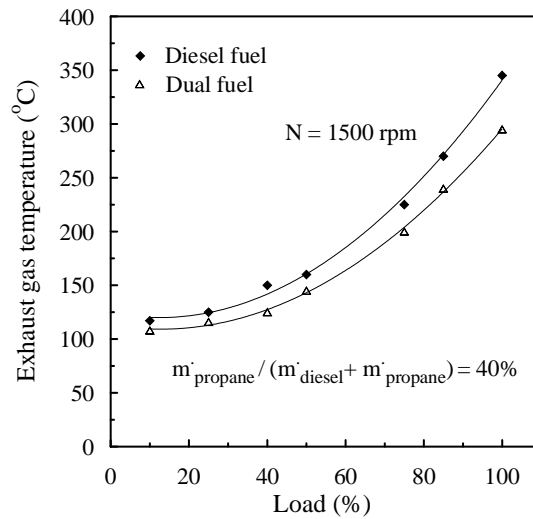


Fig. 5 Exhaust gas temperature as function of engine load at N = 1500 rpm

4.1.3 CO Emissions

The variation of carbon monoxide (CO) emissions versus engine load is shown in Fig. 6. The major production of CO occurs due to incomplete combustion because of lack of oxidants, low gas temperatures, or short residence time. In diesel operation, the increase in engine load produced higher CO in the exhaust and that due to the increasing of the amount of fuel injected per stroke which results in inadequate combustion due to greater fuel to air ratio. As shown in Fig 6, CO concentration with dual fuel operation is higher than the diesel operation. As at part loads the cylinder charge temperature is lower due to very fuel lean mixtures and that leads to incomplete combustion of propane-air mixture, very little oxidation of CO takes place consequently lesser conversion of CO to CO₂ emissions. CO emissions gradually decrease with increasing the engine load because of increasing gas-air charge mixture and the combustion from each ignition centers within the charge becomes relatively faster that deal to an increase of the temperature and oxidation reactions and as a consequence lower CO emissions. For dual fuel operation the percentage of CO in the exhaust started increasing again about 3.7% with increase the load from 85% to full load due to deterioration of combustion process because of low oxidants concentrations and the shorter reaction time.

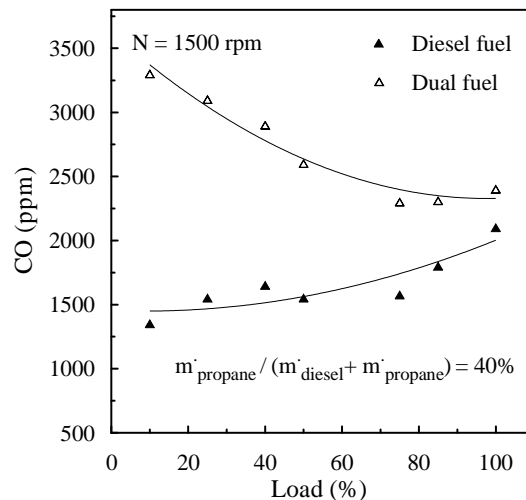


Fig. 6 Variation of CO concentration with engine load

4.1.4 SO₂ Emissions

Fig. 7 provides the variation of the sulphur dioxide emissions (SO₂) as a function of load for both diesel fuel and dual fuel operation. As the engine load was increased, SO_x emissions also increased gradually for both dual fuel operation and diesel engine because of an increase in the fuel input in the cylinder. As expected, SO₂ emissions for dual fuel operation were lower than diesel fuel reached up to 64% at full load because of the propane contains fairly nil sulfur compared to diesel fuel and release of SO₂ directly depends upon the percentage of sulphur content present in the fuel. The reduction of SO₂ emission in exhaust gas with dual fuel operation is an important advantage since the engine wear due to the present of the corrosive H₂SO₄ should reduce considerably. Hence, the engine life time is expected to be longer than normal diesel engine.

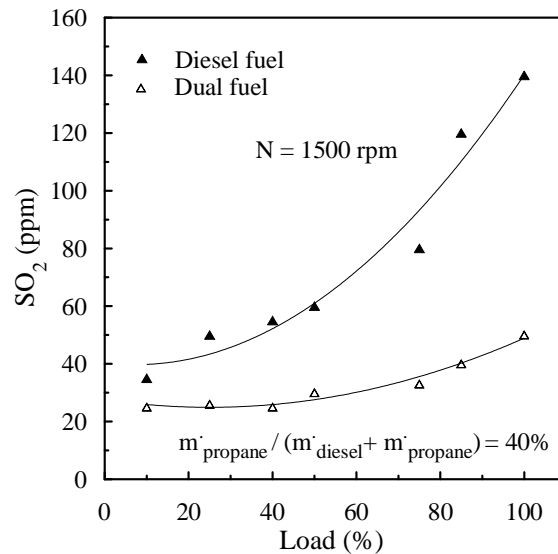


Fig. 7 Variation of SO₂ concentration with engine load

4.2 Effect of EGR on Performance and emissions at part loads for fuel #2

As explained above, engine performance and emissions suffer at low loads when operating in the dual fuel mode. The main reason for this poor light load performance is due to very lean mixtures. The lean mixtures are hard to ignite and slow to burn [18]. Therefore, in this section, the improving of the engine performance and emissions at engine speed 1500 rpm for two loads, 10% and 25% of full load have been performed by using the exhaust gas recirculation (EGR) method when operating with fuel #2-diesel blend at ratio 40%. In general, EGR is one of the most effective methods [19] used in modern engines for reducing NO_x emissions due to the lowered combustion temperature resulting from the increased inert gas in the cylinder charge. While EGR is effective in reducing NO_x, it also has adverse effects on the efficiency of the engine and may cause other pollutants. But, in dual fuel mode, EGR has positive effects on the engine performance and emissions at part load conditions as shown in Figs. 8, 9. It is found that, the fuel conversion efficiency is increased or the fuel economy is improved with increasing EGR rate gradually up to 5% and began to decrease until EGR rate of 20%. At 25% load, the fuel conversion efficiency of dual fuel operation for fuel #3 is improved from 19% without EGR to 20.1% with EGR rate 5%. These improvements possibly originate from, firstly, getting better mixture quality of the gaseous fuel air

charge, secondly, using active radicals for enhancement of combustion of the gaseous fuel air mixture (radical effect) and, thirdly, increasing the intake charge temperature (thermal effect) [6]. As the EGR increases more, at 15% and 20%, the fuel conversion efficiency tends to decrease. This decrease the result of combustion deterioration due to the dilution effect since when the EGR is increased, the gaseous fuel-air mixture gets more diluted with exhaust gases.

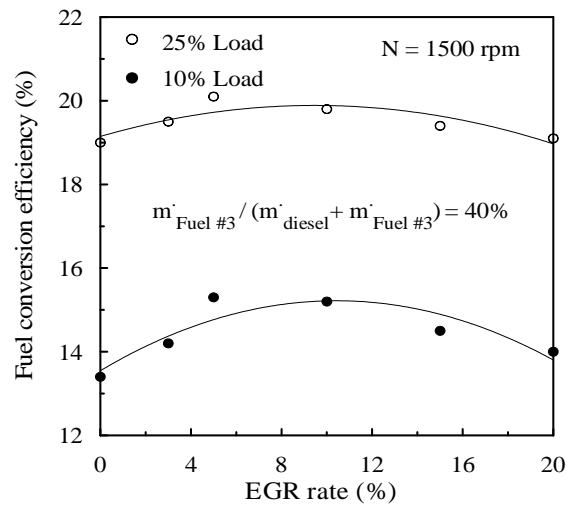


Fig. 8 Variation of fuel conversion efficiency with EGR rate

Variations of NO_x and CO emissions with the EGR rate are indicated in Fig. 9 at part loads. It can be seen that, the trend of NO_x and CO emissions versus EGR rate of the dual fuel mode is different from the conventional diesel engine [20]. As, with increasing the EGR rate to 5%, the NO_x emissions is increased from 157 ppm to 176 ppm and the CO emissions is reduced from 3140 ppm to 2600 ppm and that may be due to better combustion and the positive effects of the active radicals and thermal effect when EGR increased, as mentioned before. Increasing EGR rate above 10%, the NO_x reduction is obtained and the CO emissions increased due to an incomplete combustion, the low combustion temperature and slow down the flame caused by the diluted mixture. From the emissions data presented in the Fig. 9, a better trade-off between CO and NO_x emissions can be attained within a limited EGR rate of 5% ~ 15%.

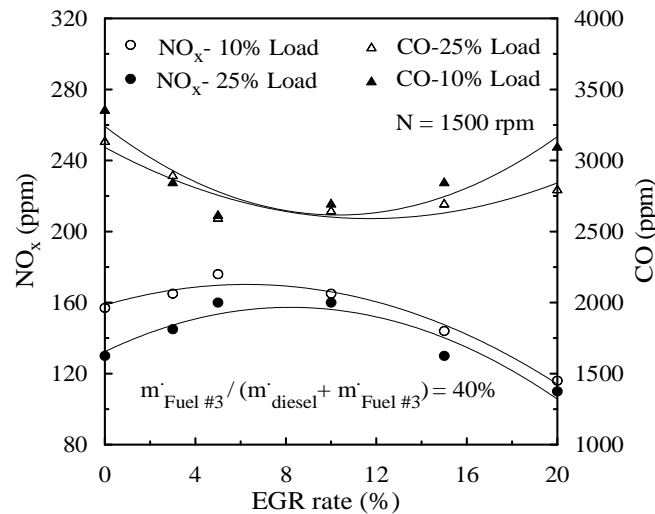


Fig. 9 Variation of NO_x and CO Emissions with EGR rate

Finally, at part loads, with EGR rate 5%, Engine performance and exhaust emission of dual fuel operation were improved for fuel #2 which has composition of 70% propane and 30% butane with the mass fraction $m_{LPG} / (m_{diesel} + m_{LPG}) = 40\%$ when compared with conventional diesel engine. At 25% load, the fuel conversion efficiency is improved from decreasing by about 5% without EGR to increasing by 0.5%, NO_x emissions are reduced from 35% without EGR to 27.6% and CO emissions changed from 100% without EGR to 67% with EGR rate 5%.

5. Conclusions

In the present work, an experimental investigation has been conducted to examine the effect of LPG /diesel blend Fuel on emissions and Performance in a dual fuel diesel engine for a range of load variations. The direct injected diesel engine was converted to pilot-injected dual fuel operation. Also, the effects of EGR on emissions and engine performance in dual-fuel operation were studied. The main results obtained in this study are as follows:

1- The test engine ran smoothly and satisfactorily up to 90% of diesel fuel substitution and the ratio of $m_{propane} / (m_{diesel} + m_{propane}) = 40\%$ substitution of the diesel fuel is the best for maintaining the high thermal efficiency comparable to a conventional engine.

2- Using pure propane-diesel (fuel #1-diesel) blend at ratio of 40%, the NO_x emissions from dual fuel operation were lowest as compared to pure diesel at overall load conditions about 21.7% and 17.7% at full and 25% load respectively.

3- Using pure propane-diesel blend at ratio of 40%, CO emissions for dual fuel operation were increased under all load conditions as compared to pure diesel especially at part loads. At full load, the CO emission was more than pure diesel by 14.3%.

4- Decrease in SO_2 emissions was observed in pure propane-diesel blend at ratio of 40%, at overall load conditions. Hence, the engine life time is expected to be longer than conventional diesel engine. SO_2 Emissions decreased about 64% and 48% at full and 25% load respectively.

5-At 25% load with EGR rate 5%, the fuel conversion efficiency of dual fuel operation for fuel #2-diesel blend is improved from 19% without EGR to 20.1%, the NO_x emissions is increased from 157 ppm to 176 ppm and the CO emissions is reduced from 3140 ppm to 2600 ppm.

6- A better trade-off between CO and NO_x emissions for fuel #2-diesel in dual fuel operation can be attained within a limited EGR rate of 5% ~ 15% at part loads.

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