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Sensitivity of dual fuel engine combustion and knocking limits to gaseous fuel composition

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Abstract

Combustion noise, knock and ignition limits data are measured and presented for a dual fuel engine running on dual fuels of Diesel and three gaseous fuels separately. The gaseous fuels used are liquefied petroleum gas, pure methane and compressed natural gas mixture. The maximum pressure rise rate during combustion is presented as a measure of combustion noise, and the knocking and ignition limits are presented as torque output at the onset of knocking and ignition failure. Experimental investigation on the dual fuel engine revealed the noise generated from combustion, knocking and ignition limits for all gases at different design and operating conditions. A Ricardo E6 Diesel version engine is converted to run on dual fuel of Diesel and the tested gaseous fuel and is used throughout the work. The engine is fully computerized, and the cylinder pressure data, crank angle data and engine operating variables are stored in a PC for off line analysis. The effects of engine speeds, loads, pilot injection angle, pilot fuel quantity and compression ratio on combustion noise, knocking torque, thermal efficiency and maximum pressure are examined for the dual engine running on the three gaseous fuels separately. The combustion noise, knocking and ignition limits are found to relate to the type of gaseous fuels and to the engine design and operating parameters.

Keywords: Dual fuel engine; LPG; Methane; CNG; Knocking; Ignition limits; Combustion noise

1. Introduction

The availability of alternative gaseous fuels has led to a worldwide spread of internal combustion engines running on the dual fuel concept. Gaseous fuels also promise to be suitable for

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higher compression engines, since it is known that they resist knock more than conventional liquid fuels, as well as producing less polluting exhaust gases if appropriate conditions are satisfied for its mixing and combustion. Therefore, it is more economical and of environmental advantage to use gaseous fuel in Diesel engines that use the dual fuel concept. There have been many published works on the use of gaseous fuels in dual fuel engines. Natural gas use in dual fuel engines has been studied from the combustion duration and ignition delay point of view [1,2] and from the performance and emissions point of view [3–8]. Combustion and thermal loading and temperature distribution have also been studied for dual engines [9–11]. Pure methane has also been studied in dual fuel engines from the flame spread limits point of view [12] and performance and emissions point of view [13]. LPG has been studied from the point of view of performance and emissions [13–16].

Noise is a pollutant from the combustion process that may have a direct effect upon observers. It may cause immediate annoyance and physiological change. Combustion noise occurs in two forms, direct and indirect. Direct noise is noise generated in and radiated from a region undergoing turbulent combustion. This is caused by a temporal fluctuation in the aggregate heat release of the reacting region. This overall fluctuation, while small, exists and generates pressure waves. The indirect noise is generated downstream of the combustion region due to interactions between streamlines of different temperatures. Depending on the device, either direct or indirect noise may be dominant. It has also been shown for some time that in Diesel engines, both the pressure–time form and the turbulence–combustion interaction may be important to the noise problem [17].

The Diesel engine is known to produce much more noise than that produced by the spark ignition engine. The noise is transmitted throughout the engine block as vibration, which can cause audible noise to a human ear at a different spectrum of frequencies. Other than airflow and mechanical noise, combustion noise is known to be a main source of noise. This is particularly true for engines that use high compression ratios, and the combustion pressure rise is fast. One of the main factors known to affect the combustion noise is the pressure rise rate during combustion [18–20]. It has also been shown [21] that the maximum rate of pressure rise is directly proportional to the sound pressure level (SPL) in decibels observed in the main chamber of the Diesel engine. Considerable efforts have been applied to have smoother and less noisy Diesel engines, and works have been published relating the Diesel engine combustion noise to the engine operating and design parameters.

Gaseous fuels are considered to be good alternative fuels for passenger cars, truck transportation and stationary engines that can provide both good environmental effect and energy security. However, as the composition of gaseous fuel candidates varies, the emission characteristics, performance and combustion noise of the gaseous engines are affected.

The purpose of the present study is to investigate the effects of differences in gas composition on engine performance, knocking and ignition limits and combustion noise characteristics of a dual fuel engine. The dual fuel engine uses Diesel fuel as pilot fuel, while the main fuel is the gaseous fuel injected in the intake manifold.

Three gaseous fuel candidates are considered here, namely pure methane (CH_4), compressed natural gas (CNG) and liquefied petroleum gas (LPG). The effects of some engine operating and design parameters e.g. load, speed, compression ratio, pilot fuel injection timing and pilot fuel mass on the combustion characteristics for the three gases, performance, knocking and ignition limits and combustion noise of the dual fuel engine shall be studied.

2. Experimental apparatus

The research engine used in the present study is the Ricardo E6 single cylinder variable compression indirect injection Diesel engine. The specifications of the engine are listed in Table 1. The engine cylinder head has a Ricardo Comet Mk V compression swirl combustion chamber. This type of combustion system consists of two parts. The swirl chamber in the head has a top half of spherical form and the lower half is a truncated cone, which communicates with the cylinder by means of a narrow passage or throat. The second part consists of special cavities cut into the crown of the piston. The engine is capable to run on 100% Diesel fuel or dual fuel. The engine is converted to run on dual fuel by introducing the gaseous fuel, pure methane, CNG mixture or LPG, separately in the present work in the intake manifold by a relevant nozzle. The gas is injected at a pressure slightly higher than atmospheric pressure.

The engine is loaded by an electrical dynamometer rated at 22 kW and 420 V. The engine is fully equipped for measurements of all operating parameters and noise data. The pressure time history is measured by a water cooled piezo-electric pressure transducer and crankshaft degree angle sensor connected to the relevant amplifiers. The liquid fuel flow rate is measured digitally by a multi-function microprocessor based fuel system, the Compuflow System. The gaseous fuel flow rate is measured by using a calibrated gas rotameter. A data acquisition system is used to collect the important data and store it in a personal computer for offline analysis. The following parameters are fed into the computer: liquid fuel flow rate, engine speed and torque and air/oil/coolant/oil/exhaust temperatures. A computer program in μMACBASIC language is written to collect the data and manage the system, and a workstation operating system has been used to run the program.

Another data acquisition system is used to collect the cylinder combustion pressure and crank angle data. The pressure signal is fed into a charge amplifier then to a data acquisition card linked to the personal computer, and the crank angle signal is fed into a degree marker shaper channel and the output fed into the acquisition card. The acquisition card could collect data at the rate of 250 kHz. A Labview program has been written to collect the data from the two channels at a sampling rate of 10,000 points per second and store the pressure and crank angle data in the computer disk for offline analysis. A computer program is written to find the pressure rise rate data at all cycle points from mid compression stroke to mid expansion stroke. The maximum value of pressure rise rate is then obtained and recorded. This value will be used to represent the

Table 1
Engine characteristics

Model	Ricardo E6
Type	IDI with the pre-combustion chamber
Number of cylinder	1
Bore × stroke (mm)	76.2 × 111.1
Cycle	4-stroke
Compression ratio	22
Maximum power (kW)	9, naturally aspirated
Maximum speed (rpm)	3000
Injection timing	35° BTDC

noise level at that operating condition. Experiments have been conducted after running the engine for some time until it reaches steady state and the oil temperature is at 60 °C ± 5, and the cooling water temperature is at 70 °C ± 5.

The data are presented as pressure rise rate in bar/degrees, output torque and thermal efficiency for the dual fuel (Diesel and gaseous fuel) for the following operating parameters:

1. Three gaseous fuels have been used separately: pure methane, CNG and LPG.
2. The engine speed is varied from 1100 to 2000 rpm.
3. The engine load is varied from minimum to 20 N m, or where knock starts.
4. The pilot fuel injection timing is varied from 20° to 45° BTDC.
5. The pilot Diesel fuel mass injected is varied from 0.26 to 0.84 kg/h.
6. The engine compression ratio is varied from 18 to 22.

3. Results and discussion

The data presented in this section includes the effect of the most important engine operating and design conditions, viz. engine speed, load, pilot fuel injection, quantity of pilot fuel mass and engine compression ratio on the thermal efficiency, combustion noise and knocking torque of the dual fuel engine running on three gaseous fuels separately.

A typical pressure time diagram collected from the engine is illustrated in Fig. 1. The pressure time data is used to calculate the pressure rise rate or slope of the pressure time curve at each data point. The pressure rise rate is then plotted against time for the same time period. A typical pressure rise rate against time is also shown in Fig. 1 for the same pressure data shown. It can be seen from this figure that the slope of the pressure time curve increases during the compression

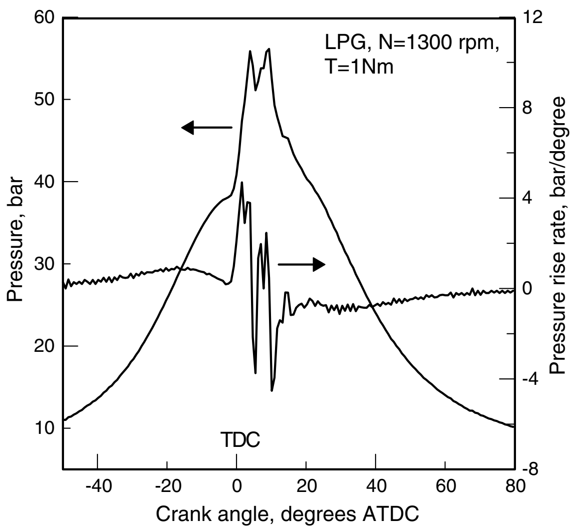

Fig. 1. Typical combustion pressure and pressure rise rate.

and combustion period until it reaches the highest value at a certain crank angle, and then the slope starts to decrease, while the pressure is still increasing, till the maximum pressure point. The slope then becomes zero at that point and then negative afterwards during the expansion stroke. The maximum value of this pressure rise rate data is then taken and recorded, in bars/degrees, to represent the combustion noise at the corresponding conditions.

3.1. Effect of load

The effects of the amount of gaseous fuel, as a fraction of the total amount of fuel, on the output torque, thermal efficiency, maximum pressure rise rate and maximum combustion pressure are illustrated in Fig. 2(a)–(d), respectively. During these experiments, the following parameters

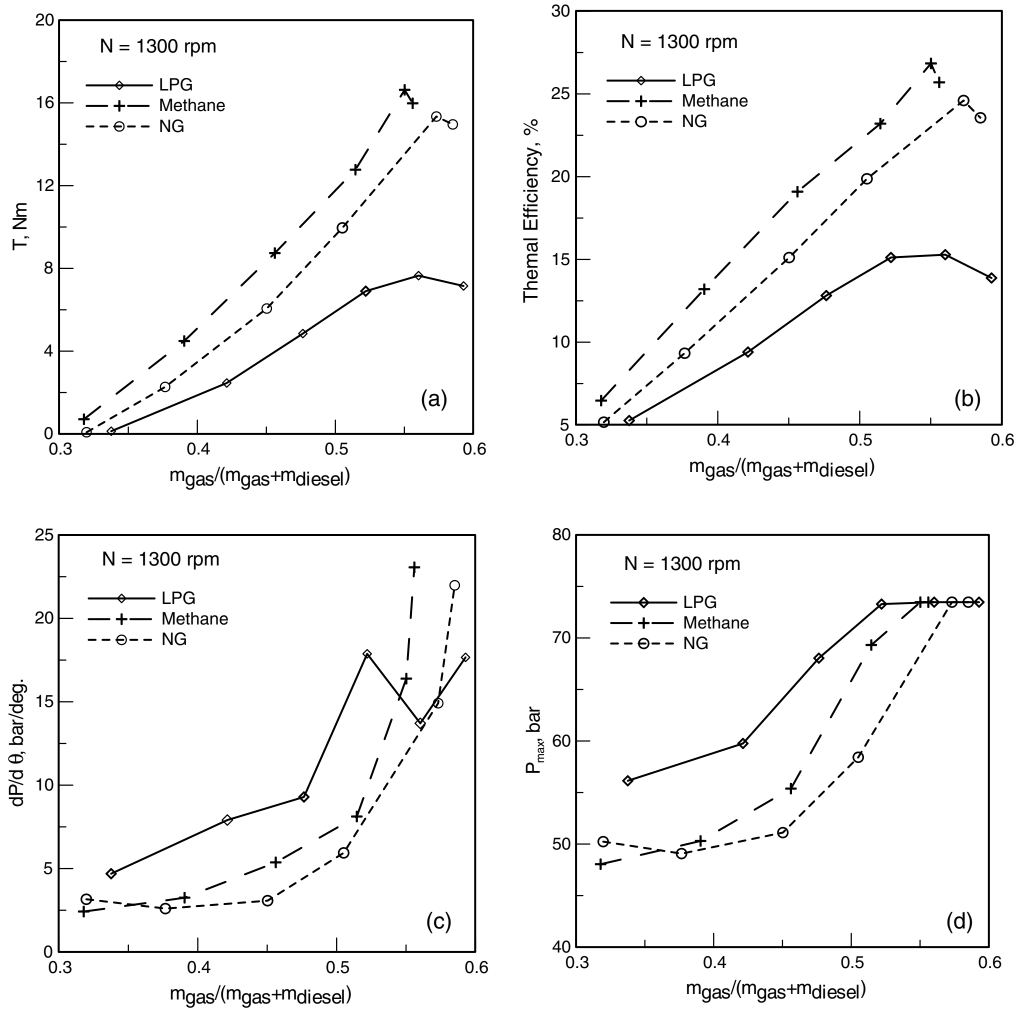

Fig. 2. Effects of mass of gaseous fuel used on performance and noise: $N = 1300$ rpm, IT = 35° BTDC, CR = 22, $m_d = 0.37$ kg/h.

were kept constant: engine speed 1300 rpm, pilot fuel injection timing 35° BTDC, mass of pilot fuel 0.37 kg/h and compression ratio 22.

The load and thermal efficiency variations with gaseous fuel fraction are shown in Fig. 2(a) and (b). It may seen that for the three gases used, LPG, methane or natural gas mixture, the output torque increases with increasing the amount of gaseous fuel used. During these three experiments, the amount of liquid Diesel fuel has been kept constant. However, it may be noticed that the output torque and the thermal efficiency for when the dual fuel engine used pure methane is higher than for the natural gas mixture which is higher than for LPG. This may be postulated to be due to the increased lower heating value for methane compared to the natural gas mixture and LPG. LPG has the lowest heating value among the three fuels used, as may be seen in Table 2. The dual fuel engine, for all fuels used, however, suffers from low thermal efficiency at part load, and then it increases with increasing load by increasing the mass of gaseous fuel admitted.

The mass of gaseous fuel has been increased until the engine starts to knock and the output power and thermal efficiency, as may be seen from this figure, start to decrease. When the engine used LPG as a main fuel, the knock starts at lower torque, followed by natural gas then methane. This early knocking onset of the LPG case could be due to the lower auto-ignition temperature of the LPG (about 400 °C), followed by the higher auto-ignition temperature of natural gas with the methane gas having the highest auto-ignition temperature (about 650 °C), see Table 2. This has been shown also by Ref. [11] from their combustion bomb measurements for ignition delay of gaseous fuels, namely that the methane has higher auto-ignition temperature and more ignition delay than natural gas followed by high ethane natural gas. As the mass of gaseous fuel introduced with air increases and, hence, the maximum combustion temperature increases, the gaseous fuel existing in the combustion chamber would be more susceptible to self-ignition. The engine started to knock much earlier when LPG is used in the dual fuel engine, approximately at an output torque of 8 N m, where the knocking torque was about 16 N m for natural gas.

The maximum pressure rise rate and maximum combustion pressure variations with the gaseous mass fraction may be seen in Fig. 2(c) and (d). As the amount of gaseous fuel increases, the maximum combustion pressure and pressure rise rate increase for all three gaseous fuels used. Increasing the load at constant speed resulted in an increase in the mass of gaseous fuel admitted to the engine, since the pilot mass injected is constant at all loads. The increase in the mass of gaseous fuel may then cause an increase in the ignition delay period of the pilot Diesel, which then auto-ignites and starts burning the gaseous fuel at a higher rate of pressure rise. This has been

Table 2
Fuels chemical characteristics

Property	Methane CH_4	Natural gas	LPG	Diesel fuel
Main constituents, % by weight	75 C, 25 H_2	76 C, 24 H_2	C_3H_8, C_4H_{10}	86 C, 14 H_2
Lower heating value, MJ/kg	50	47.7	46.1	42.5
Density at 0 °C and 1013 mbar, kg/m^3	0.72	≈0.83	2.25	815
Auto-ignition temperature	650	≈500	≈400	≈250
Flammability limits: % volume of fuel in air, lower:higher	5%:15%	–	1.5%:15%	≈0.6:≈7.5%
Theoretical air requirement, kg/kg	17.2	16.6	15.5	14.5

shown by Ref. [22] on dual fuel where natural gas was admitted in the inlet air manifold. They have shown that the ignition delay of the pilot Diesel was significantly increased by the presence of natural gas. Their data show that the presence of 2% methane in the intake air doubles the ignition delay of the Diesel fuel. This increase in delay period is partly due to the change in the specific heat of the compressed mixture that resulted in lowering the compression temperature. The other reasons may be the reduced oxygen concentration due to the air displacement by methane and a chemically inhibiting effect of the presence of methane on the Diesel liquid fuel reaction rate as suggested by Ref. [22]. With the increase in load in the present engine, the amount of gas increased, and hence, these two results may affect the ignition delay.

LPG, however, produces the highest pressure rise rate as compared to methane and the natural gas mixture prior to knocking, Fig. 2(c), because of its high tendency to self ignite and produce knocking combustion. The maximum pressure for the LPG case also appears to be the highest, followed by methane and then natural gas mixture, Fig. 2(d). This may be postulated to be due to the early ignition of the LPG that produces higher maximum pressure before top dead centre, which tends to reduce the torque output produced for LPG, Fig. 2(a).

3.2. Effect of engine speed

The effect of engine speed on output torque, thermal efficiency, maximum pressure rise rate and maximum combustion pressure may be seen in Fig. 3(a)–(d), respectively. During these experiments, the following parameters were kept constant: pilot fuel injection timing 35° BTDC, mass of pilot fuel 0.37–0.47 kg/h and compression ratio 22.

The load and thermal efficiency variations with engine speed are shown in Fig. 3(a) and (b). As occurred with the load test, it may be seen that the LPG produced the lowest torque output and thermal efficiency as compared to methane or the natural gas mixture. The torque output and efficiency was highest for methane gas. The thermal efficiency also improves with increasing engine speed.

The maximum pressure rise rate and maximum combustion pressure variations with the engine speed are depicted in Fig. 3(c) and (d). Generally, as the engine speed increases, the pressure rise rate ($dP/d\theta$) decreases for the three dual fuel cases. However, the pressure rise rate is highest for the dual fuel engine using methane, followed by LPG and followed by natural gas at almost all engine speeds, and it follows a similar trend in all cases.

It has also been shown in Ref. [21] that the combustion noise ($dP/d\theta$) decreased when the engine speed increases. The authors measured the pressure rise rate in the combustion chamber of an IDI Diesel engine and related it to the SPL in decibel (dB) and also measured the SPL in the intake and exhaust manifold. They have shown a reduction in ($dP/d\theta$) as the engine speed increased. At the same time, the SPL has increased in the intake and exhaust manifold as engine speed increases. They have also shown a decrease in the heat release rate ($dQ/d\theta$) with the increase in engine speed. The reduction in combustion noise was postulated to be due to the reduction in the maximum rate of heat release. The difference in maximum pressure rise rate, however, becomes smaller for the three gases at higher engine speeds. The maximum combustion pressure for methane is highest, Fig. 3(d), as the maximum pressure rise rate is highest. This may have produced faster combustion before top dead center and produced higher maximum pressure.

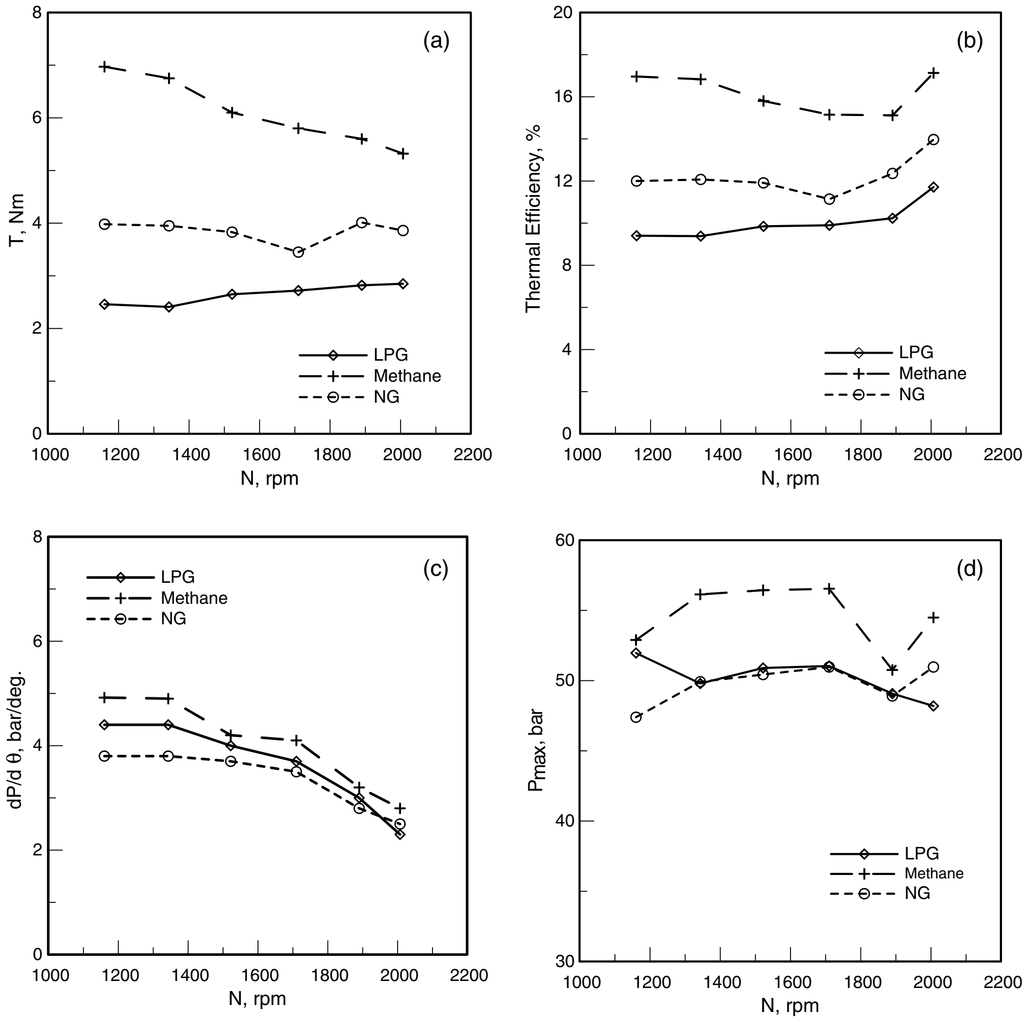

Fig. 3. Effects of engine speed on performance and noise: IT = 35° BTDC, CR = 22, m_d = (0.37–0.47) kg/h.

3.3. Effect of pilot fuel injection timing

The effect of pilot fuel injection timing on output torque, thermal efficiency, maximum pressure rise rate and maximum combustion pressure may be seen in Fig. 4(a)–(d), respectively. The results shown are at constant engine speed of 1300 rpm and compression ratio of 22. For the dual fuel engine burning the three gases, the pilot rack position was constant, and the mass of pilot fuel was 0.37 kg/h and the amount of methane gas was fixed.

It may be seen that the torque output varies with the pilot fuel injection timing almost with the same trend for the three gaseous fuels used. The torque output is highest at certain timings, and it decreases at earlier or later timing. The LPG produces the least torque output, Fig. 2(a), as it produces the highest pressure rise rate, Fig. 4(d), due to its high tendency to self ignite earlier than

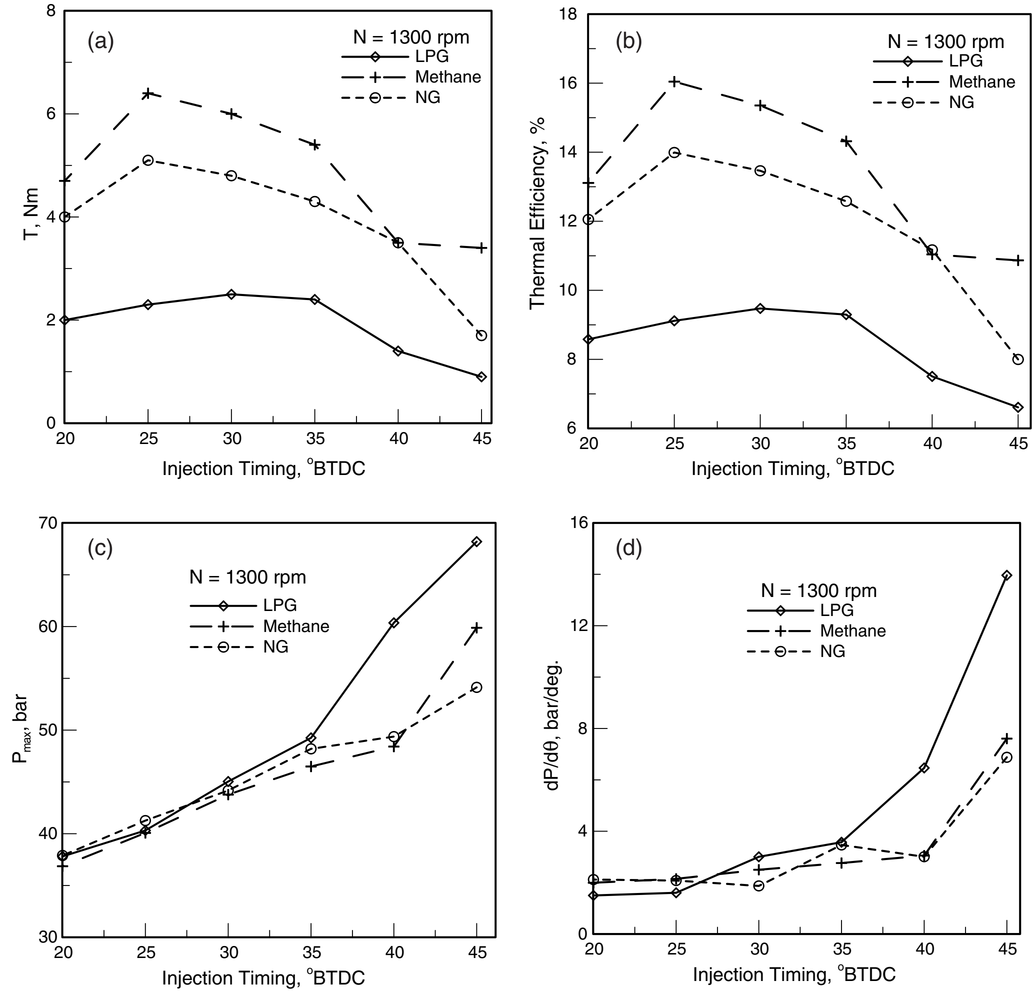

Fig. 4. Effects of pilot fuel injection timing on performance and noise: $N = 1300$ rpm, CR = 22, $m_d = 0.37$ kg/h.

the other gaseous fuels. However, the highest torque output for methane and natural gas occurs when the injection timing was 25° BTDC, while for LPG it occurs at 30° BTDC. Earlier injection of pilot fuel causes the maximum pressure to increase, Fig. 4(c), and to occur before top dead centre in the compression stroke, which, in turn, reduces the maximum pressure during the expansion stroke and then the torque output is reduced.

The combustion noise, as may be seen in Fig. 4(d), generally increases as the pilot Diesel injection advance increases for all dual fuel cases. This may be attributed to the increase in ignition delay of the Diesel fuel, since the liquid fuel is injected earlier in lower air pressure and temperature. The longer delay period would result in a higher pressure rise rate ($dP/d\theta$). This has also been shown by Ref. [20] as they presented the pressure rise rate in the pre-combustion chamber for 100% Diesel and all Diesel–methanol blends to increase as the injection advance increased. With the presence of gaseous fuel in the mixture, any advance in pilot injection would result in a longer ignition delay period, and the pressure rise rate is expected to increase. For the late injection of pilot fuel, 20–25° BTDC, the combustion noise is low for all dual fuel cases. However, as the injection advance increases, 25–40° BTDC, the dual fuel engine produced higher rates of pressure rise ($dP/d\theta$).

3.4. Effect of pilot fuel quantity

The effects of pilot fuel quantity on the output torque, thermal efficiency, maximum pressure rise rate and maximum combustion pressure are illustrated in Fig. 5(a)–(d), respectively. During these experiments the following parameters were kept constant: engine speed 1300 rpm, pilot fuel injection timing 35° BTDC and compression ratio 22.

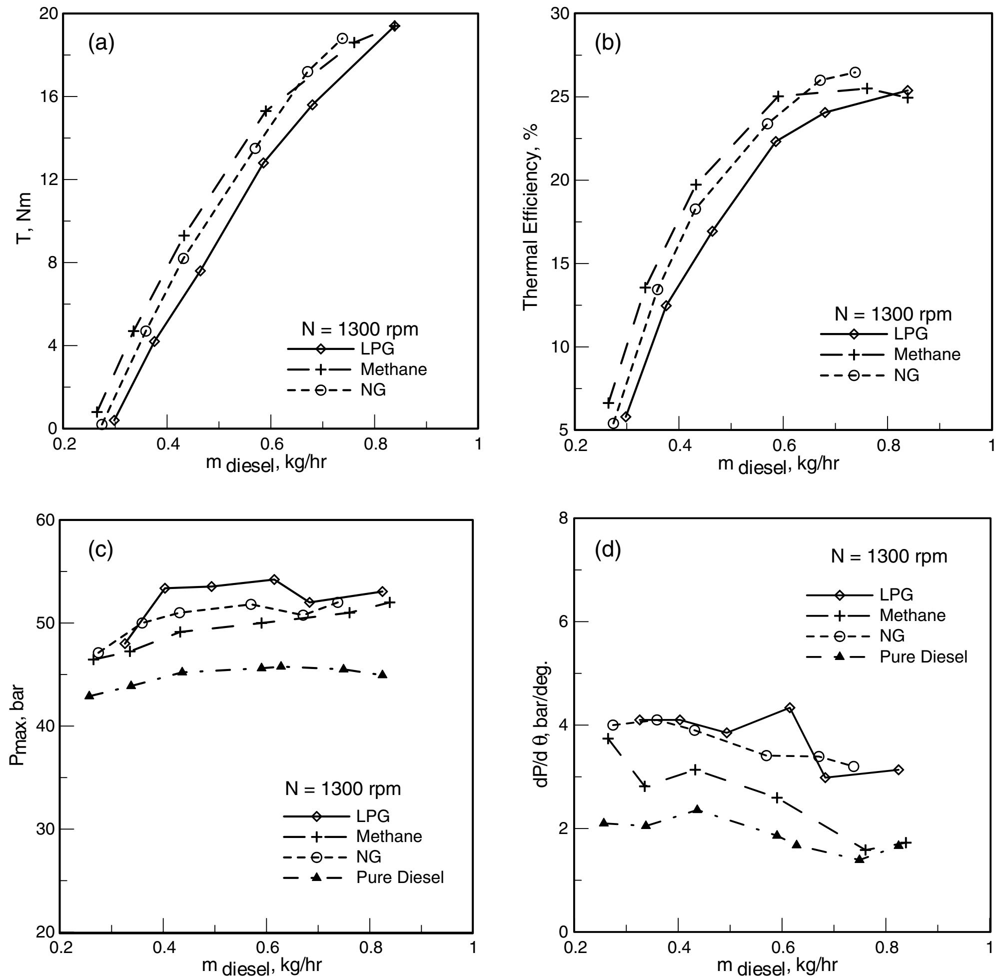

Fig. 5. Effects of pilot fuel mass on performance and noise: $N = 1300$ rpm, IT = 35° BTDC, CR = 22.

It may be seen from Fig. 5(a) and (b) that increasing the quantity of pilot Diesel fuel increases the torque output and, hence, thermal efficiency for the three gaseous fuels used. Increasing the pilot Diesel fuel for the three cases results in greater energy release on ignition, improved pilot injection characteristics, larger size of pilot mixture envelope with greater entrainment of the gaseous fuel, a larger number of ignition centers requiring shorter flame travels and a higher rate of heat transfer to the unburned gaseous fuel–air mixture [12]. These factors tend to increase the power output and thermal efficiency of the dual fuel engine [23]. Similar to previous experiments, LPG produced the least torque output and thermal efficiency while methane produced the highest torque and efficiency.

Increasing the pilot fuel mass also resulted in higher maximum combustion pressure as may be seen in Fig. 5(c). An experiment with the engine running pure Diesel at the same Diesel fuel quantity is also shown in the same figure for comparison. For the dual fuel engine, the maximum pressure is always higher than in the Diesel fuel case due to the combustion and extra heat released from gaseous fuels.

The maximum pressure rise rate, as seen in Fig. 5(d), is generally reduced when the pilot fuel quantity is increased. The decrease in the combustion noise ($dP/d\theta$) when the pilot fuel mass is first increased may be postulated to be due to the increase in flame volume resulting from, the increase in pilot fuel mass, which would burn the gaseous fuel smoothly and at a lower rate of combustion. The increase in the initial pilot flame volume may have caused the air/gas mixture to ignite with more mini flames with smaller air/fuel mixture pockets ignited. However, when the pilot fuel mass increased beyond a certain amount, the ignition delay period of the pilot Diesel may increase and may increase the pressure rise rate ($dP/d\theta$) for the gas/air mixture [10].

3.5. *Effect of engine compression ratio on knock limits and ignition failure*

Fig. 6(a)–(c) depict the effect of compression ratio on knock onset and ignition failure for the three gaseous fuels used, while Fig. 7(a)–(c) illustrate this effect on the maximum pressure rise rate.

For LPG, Fig. 6(a) shows the occurrence of knock onset and ignition failure at the three compression ratios of 18, 20 and 22. It may be seen that for the higher compression ratio of 22, knock starts very early at an engine torque of about 8.1 N m, while any increase in gaseous fuel quantity increases the knocking intensity and starts to reduce the output torque until ignition failure occurs at about 7.85 N m and output then drops sharply. As the compression ratio is reduced to 20, the torque at which knocking starts is shifted to a higher value of about 17.6 N m, and ignition failure occurs at about 17 N m. For the lower compression ratio of 18, the knocking limit is shifted to about 20 N m, and the ignition failure is shifted to 18.5 N m. It may be concluded that reducing the compression ratio has resulted in retarding the occurrence of knock onset in the dual fuel engine (from 8.1 to 17.6 to 20 N m) and also extended the ignition limits greatly (from 7.85 to 17 to 18.5 N m). This may be postulated to be due to the early knocking at high compression ratios associated with higher pressures and temperatures and lower self ignition temperatures of LPG. For extended ignition limits and knock free operation of the dual fuel engine, the compression ratio has to be then reduced to lower values.

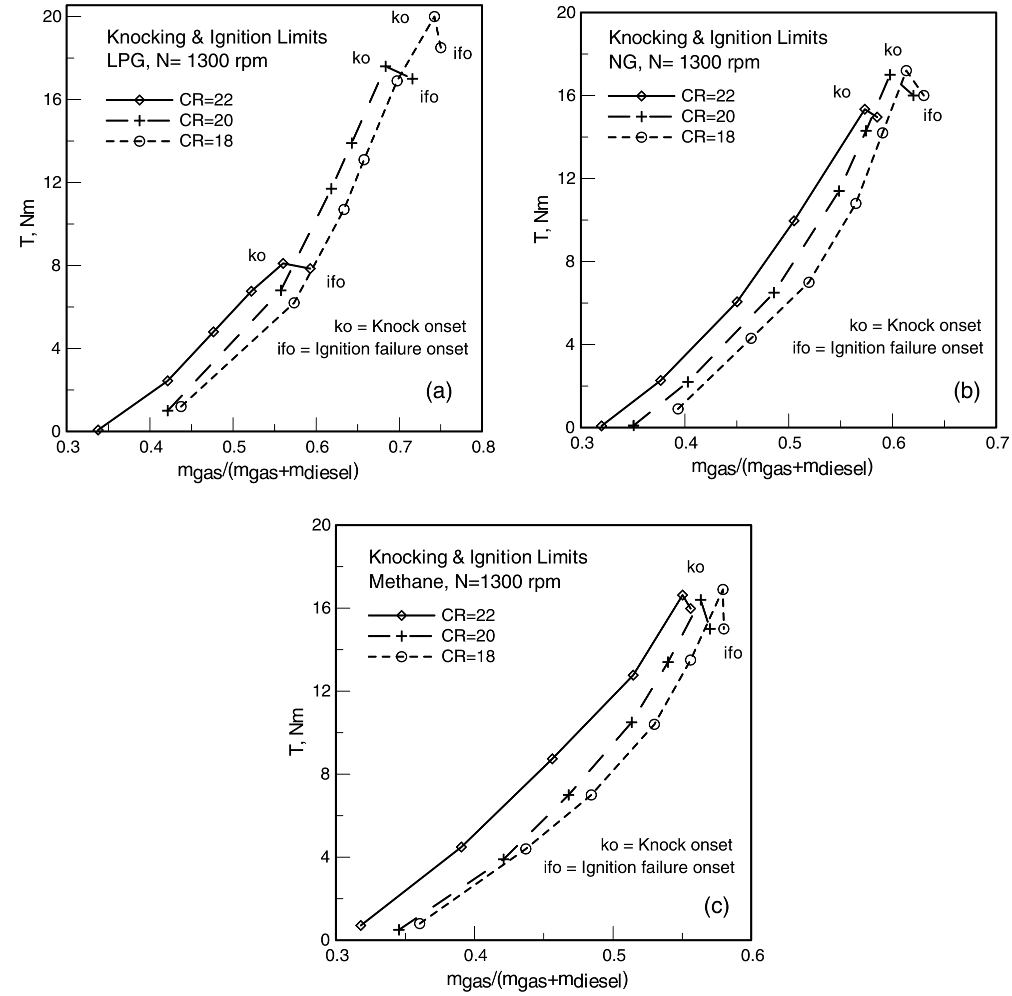

Fig. 6. Effect of compression ratio on knock and ignition limits for LPG, methane and natural gas: $N = 1300$ rpm, IT = 35° BTDC, $m_d = 0.37$ kg/h.

For the natural gas mixture and methane cases, Fig. 6(b) and (c) illustrate that they have similar trend to LPG with the only difference at the compression ratio of 22. As LPG has the lowest self ignition temperature, it starts knocking and ignition fails at lower engine torque compared to the other gases. Although reducing the compression ratio decreases the torque output at the same gaseous fuel amount, it extends the limits of knock free operation and the ignition limits.

Fig. 7(a)–(c) illustrate the maximum pressure rise rate at different compression ratios for the three fuels used. It may be seen that increasing the compression ratio generally increases the combustion noise due to the higher self ignition possibility of the gaseous fuels at higher pressures and temperatures. As the compression ratio is reduced, the combustion noise is also reduced, and the ignition limits are extended.

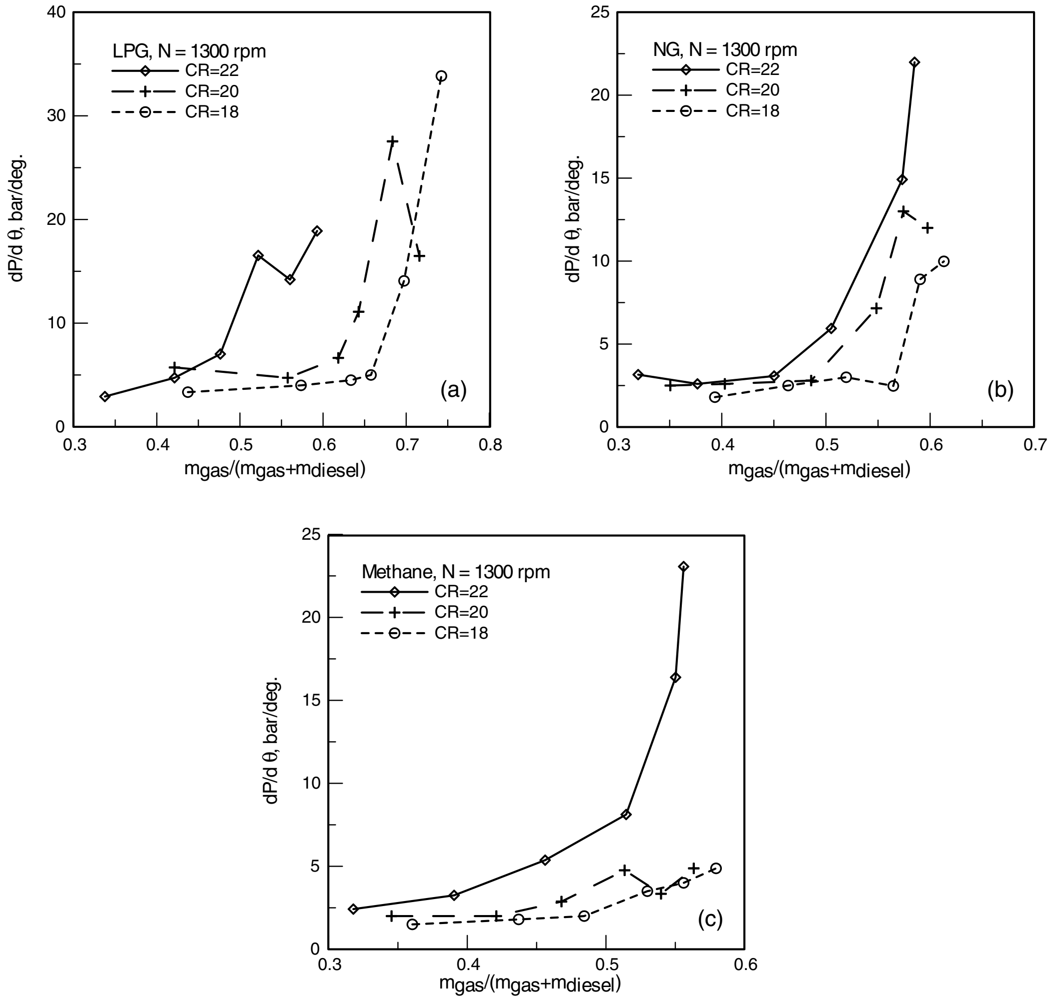

Fig. 7. Effect of compression ratio on combustion noise for LPG, methane and natural gas $N = 1300$ rpm, IT = 35° BTDC, $m_d = 0.37$ kg/h.

4. Conclusions

From the experimental study conducted on the dual fuel engine using three different gaseous fuels, the following conclusions may be drawn:

1. The dual fuel engine that utilizes methane produces higher power and efficiency than that using natural gas, followed by LPG.
2. The dual fuel engine starts to knock early when using LPG as the main fuel, followed by the natural gas mixture, and then methane gives the highest resistance to knock.
3. The onset of knock of the dual fuel engine is associated with a drop in thermal efficiency and output power.

4. Increasing the mass of gaseous fuel used increases the combustion noise and maximum pressure for the three gaseous fuels.
5. Increasing the engine speed or load increases the thermal efficiency of the dual fuel engine.
6. Increasing the engine speed reduces the combustion noise for the dual fuel engine.
7. The engine using LPG as the main gaseous fuel produces the highest combustion noise, followed by both methane and natural gas.
8. Advancing the pilot fuel injection timing reduces the torque output, reduces the thermal efficiency and increases the maximum pressure and maximum pressure rise rate.
9. Increasing the pilot fuel quantity increases the torque output, thermal efficiency and maximum pressure for the three gases, yet it reduces the combustion noise for the three gases. However, the combustion noise generated is greater than in the pure Diesel mono-fuel case.
10. Knock starts earlier when a high compression ratio is used in the dual fuel engine, and this is more notable for LPG. Dual fuel engines with non-knocking operation should use lower compression ratios.
11. The onset of ignition failure and combustion noise are affected by the compression ratio and the type of gaseous fuel used.

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