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Effect of exhaust gas recirculation on some combustion characteristics of dual fuel engine

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Abstract

Combustion pressure rise rate and thermal efficiency data are measured and presented for a dual fuel engine running on a dual fuel of Diesel and compressed natural gas and utilizing exhaust gas recirculation (EGR). The maximum pressure rise rate during combustion is presented as a measure of combustion noise. The experimental investigation on the dual fuel engine revealed the noise generated from combustion and the thermal efficiency at different EGR ratios. A Ricardo E6 Diesel version engine is converted to run on a dual fuel of Diesel and compressed natural gas and having an exhaust gas recycling system is used throughout the work. The engine is fully computerized, and the cylinder pressure data and crank angle data are stored in a PC for offline analysis. The effects of EGR ratio, engine speeds, loads, temperature of recycled exhaust gases, intake charge pressure and engine compression ratio on combustion noise and thermal efficiency are examined for the dual fuel engine. The combustion noise and thermal efficiency of the dual fuel engine are found to be affected when EGR is used in the dual fuel engine.

Keywords: Dual fuel engine; Natural gas fuel; Pressure rise rate; Noise; Thermal efficiency; Exhaust gas recirculation

1. Introduction

The use of natural gas in Diesel engines has both economic and environmental advantages. The economic benefit stems from the availability of natural gas in huge quantities in many parts of the world. The use of the gaseous fuel locally would save the use of liquid fuels, such as Diesel or

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gasoline. Secondly, natural gas gives high resistance to knock when used as a fuel in internal combustion engines. It is, therefore, suitable for engines of high compression ratio with a possible improvement of thermal efficiency [1]. The environmental advantage stems from reduced particulate matter in the exhaust, as it contains less dissolved impurities (e.g. sulphur compounds) than petroleum fuels, and the low carbon-to-hydrogen ratio of the gas is associated with lower emissions of carbon dioxide [2].

The use of natural gas in Diesel engines is possible by using a dual fuel of Diesel and natural gas [3]. The gaseous fuel is mixed with the intake air in the intake manifold, which then undergoes a multi-point ignition due to the compression ignition and combustion of a pilot Diesel fuel spray. Then, flame propagation occurs through the pre-mixed natural gas mixture. Thus, dual fuel operation with natural gas fuel can yield a high thermal efficiency, almost comparable to the Diesel engine at higher loads. However, engine performance and emissions suffer at low loads when operating in the dual fuel mode [4–6]. One reason for this is the resulting very lean mixtures at low loads. The lean mixtures are hard to ignite and slow to burn. The use of exhaust gas recirculation (EGR) is suggested as a method of improving the engine performance at low load and reducing the emissions of such engines. By increasing the intake charge temperature, hot EGR could promote better combustion. Some of the unburned fuel can be re-burned with this method, however, NO_x levels can possibly go up. To counter this tendency of hot EGR, cooled EGR may be beneficial. NO_x levels may be much reduced by using cooled EGR in such engines [7].

The use of EGR in a dual fuel engine is, therefore, a promising method for improving part load operation and reducing the exhaust emissions of NO_x. However, when EGR is used, it may change the rate of combustion or the rate of pressure rise inside the combustion chamber, which is related to another dangerous pollutant, i.e. combustion noise.

Noise is a pollutant of 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 known for some time that in diesel engines, both the pressure–time form and the turbulence–combustion interaction may be important to the noise problem [8].

A Diesel engine is known to produce much more noise than that produced by a spark ignition engine. Noise is transmitted throughout the engine block as vibration, which can cause audible noise to the 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 that is known to affect the combustion noise is the pressure rise rate during combustion, [9–11]. It has also been shown [12] that the maximum rate of pressure rise is directly proportional to the sound pressure level (SPL) in decibels observed in the main chamber of a 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. However, the combustion noise and thermal efficiency data for the dual fuel engine that utilizes EGR is lacking.

In the present study, the combustion noise and thermal efficiency are related to some operating and design parameters for a dual fuel engine. The pressure rise rate and thermal efficiency are measured and analyzed at different engine loads, engine crankshaft speeds, intake charge pressures, EGR temperatures and two compression ratios.

2. Engine test rig description

The test rig 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 of running on 100% Diesel fuel or dual fuel. The engine is converted to run on dual fuel by introducing the gaseous fuel, pure methane 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 EGR system consists of a piping system taken from the engine exhaust pipe, a filter to prevent smoke from re-entering the cylinder, an orifice meter to measure the flow rate of the exhaust gases and a control valve to change the quantity of gases being recycled. A schematic diagram of the EGR system may be seen in Fig. 1. The filter element has to be changed from time to time to reduce the smoke entering the engine to a level as low as possible. Both glass wool and steel wool have been tried, and they acted well as the filter elements.

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 combustion noise data. The pressure time history is measured by a water cooled piezoelectric pressure transducer and crankshaft degree angle sensor connected to relevant amplifiers. The liquid fuel flow rate is measured digitally by a multi-function microprocessor based fuel system, Compuflow System. The gaseous fuel flow rate is measured by using an orifice meter connected to an electronic partial pressure transducer that is connected to a digital pressure meter. The flow rate of recycled exhaust gases is measured by using an orifice meter connected to an inclined manometer. A data

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	four stroke
Compression ratio	22
Maximum power (kW)	9, naturally aspirated
Maximum speed (rpm)	3000
Injection timing	35° BTDC

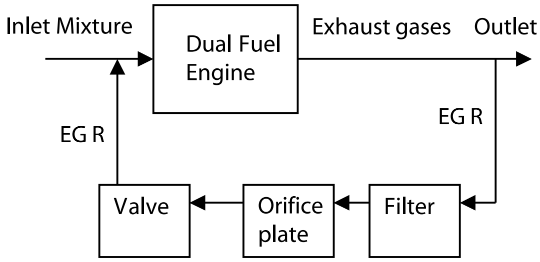

Fig. 1. Exhaust gas recirculation system.

acquisition system is used to collect the important data and store it in a personal computer for off line analysis. The following parameters are fed into the computer: cylinder pressure data, crank angle degrees signal, liquid and gaseous fuel flow rate data, engine speed and torque, and air/oil/coolant/recycled 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.

The pressure signal is fed into a charge amplifier and then to a data acquisition card linked to the personal computer, and the crank angle signal is fed into a degree marker shape channel with the output fed into the data acquisition card. The acquisition card could collect data at the rate of 250 kHz. The pressure and crank angle data is stored in the computer disk for off line analysis by using a Labview acquisition program. 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 noise level at that operating condition. Experiments have been conducted after running the engine for some time, until it reaches steady state, oil temperature is at 60 ± 5 °C and cooling water temperature is at 70 ± 5 °C.

Combustion noise data (as pressure rise rate in bar/degrees) and thermal efficiency are presented for the dual fuel (Diesel and methane) engine with and without exhaust gas recycle for the following operating parameters:

(i) The engine speed is varied from 1200 to 2400 rpm.
(ii) The engine load is varied from 4 to 18 N m.
(iii) The exhaust gas recirculation ratio, as mass of exhaust gases recycled divided by total inlet charge is varied from 0% (no EGR) to 15% in steps of 5%.
(iv) The temperature of the recycled exhaust gases is varied at two levels, 30 °C (for cold EGR) and 55 °C (for hot EGR).
(v) The intake charge pressure is varied from 1 to 1.4 atm.
(vi) The compression ratio is varied from 19 to 22.

3. Results and discussion

The data presented in this section includes the effect of the most important operating conditions, viz. engine speed and load, on the thermal efficiency and combustion noise of the dual fuel

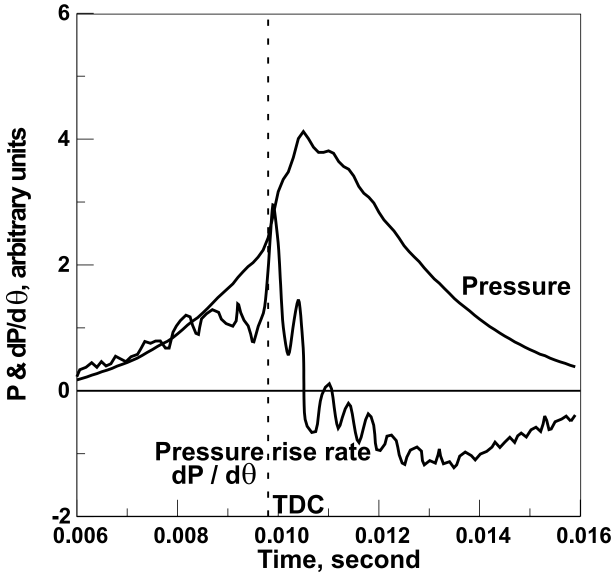

Fig. 2. Typical pressure and pressure rise rate diagram against time.

engine. The results are presented for normal operation of the dual fuel engine, e.g. without EGR, and, when EGR is used, at mass ratios of 5%, 10% and 15% of the total inlet mixture (exhaust gases, air and natural gas).

A typical pressure time diagram collected from the engine is illustrated in Fig. 2. 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. 2 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 and combustion period until it reaches the highest value at a certain crank angle, then the slope starts to decrease, while the pressure is still increasing, until the maximum pressure point is reached. The slope then becomes zero at that point and negative afterwards during the expansion stroke. The maximum value of this pressure rise rate data is then taken and recorded, in bars/degree, to represent the combustion noise at the corresponding conditions.

4. Effect of engine speed

4.1. Thermal efficiency

The effect of engine speed on thermal efficiency at different EGR ratios and at a compression ratio of 22 is shown in Fig. 3. The engine is running at part load conditions, and the efficiency increased with increasing engine speed from 1200 to 2400 rpm. As the EGR is increased from 0% to 5%, the efficiency tends to increase slightly, especially at low speeds up to 1600 rpm. This may

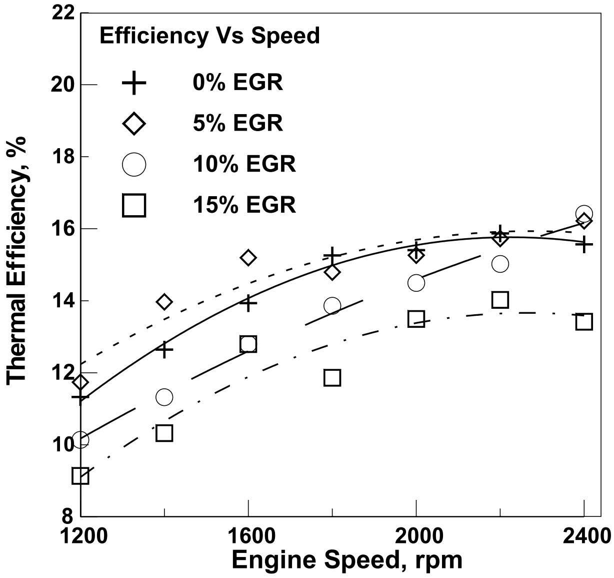

Fig. 3. Effect of engine speed on thermal efficiency.

be attributed to the improved combustion of natural gas as the inlet temperature increases when EGR is introduced, especially at part load [7].

As the EGR increases more, at 10% and 15%, the thermal efficiency tends to decrease at all engine speeds. This decrease in thermal efficiency could be the result of combustion deterioration when the EGR is increased and the gaseous fuel–air mixture gets more diluted with exhaust gases. It has been shown by Refs. [13,14] that when more EGR is introduced in a Diesel engine, the dilution effect was the most significant one influencing the combustion process and formation of emissions. The dilution effect occurs when the oxygen fraction in the inlet charge is reduced due to replacement with exhaust gases.

4.2. Pressure rise rate

The effect of engine speed on the maximum pressure rise rate may be seen in Fig. 4 for different EGR ratios. The pressure rise rate ($\mathrm{d}P/\mathrm{d}\theta$) tends generally to decrease with increasing engine speed from 1200 to 2400 rpm. The decrease in maximum pressure rise rate shows a similar trend at almost all amounts of EGR used.

It has also been shown by Ref. [12] that the combustion noise ($\mathrm{d}P/\mathrm{d}\theta$) decreased when the engine speed increases. The authors [12] measured the pressure rise rate in the combustion chamber of an IDI Diesel engine running on pure Diesel 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 ($\mathrm{d}P/\mathrm{d}\theta$) as the engine speed increased. At the same time, the SPL has increased in the intake and exhaust manifold as the engine speed increases. They have also shown a decrease in the heat release rate ($\mathrm{d}Q/\mathrm{d}\theta$) with increase in engine speed. The reduction in combustion noise was postulated to result from the reduction in the maximum rate of heat release.

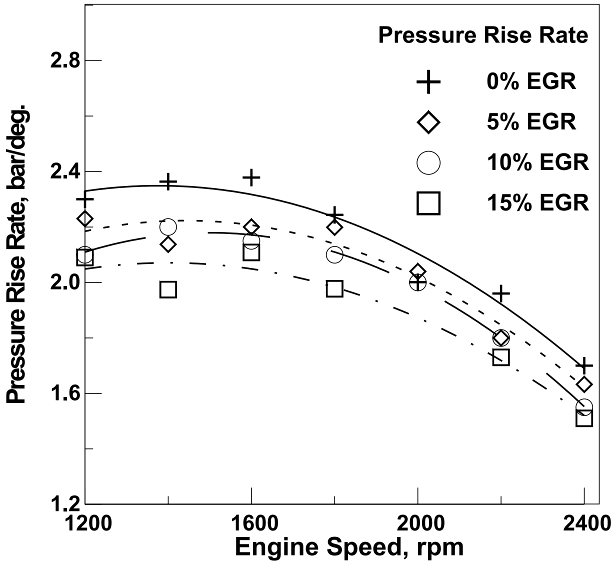

Fig. 4. Effect of engine speed on maximum pressure rise rate.

It is also shown in Fig. 4 that as the EGR used is increased from 0% to 15%, the combustion noise has decreased at most engine speeds. Previous work [13] has examined the effect of using diluting CO_2 in the intake mixture of a Diesel engine. The increased dilution effect of the CO_2 has shown a progressive shift in the heat release rate pattern. This shift in heat release showed a delay of the combustion phases and increased ignition delay. The ignition delay increase provided more time for the fuel to mix with the oxidizer, which could have increased the amount of pre-mixed fuel. However, the reduction in oxygen fraction reduced the intensity of the pre-mixed combustion and, thereby, somewhat offset the effect of extra pre-mixed fuel. This was clearly shown by the reduction in the peak heat release rate when CO_2 replaced oxygen.

5. Effect of load

5.1. Thermal efficiency

The effect of load on the thermal efficiency of the dual fuel engine at different cold EGR ratios and at a compression ratio of 22 is shown in Fig. 5 at an engine speed of 1200 rpm and in Fig. 6 at an engine speed of 1600 rpm. It may be seen that the general increase in thermal efficiency of the dual fuel engine is shown for all EGR ratios used as well as for the no-EGR case. However, as the EGR amount is increased from 0% to 5%, there has been some increase in thermal efficiency at almost all loads. This is similar to that of the engine speed test described above and is attributed to the improved combustion of natural gas as the inlet temperature increases when EGR is introduced. It has been shown [13] that the effect of using EGR in a Diesel engine has three effects, dilution effect, chemical effect and thermal effect. The chemical effect is associated with the

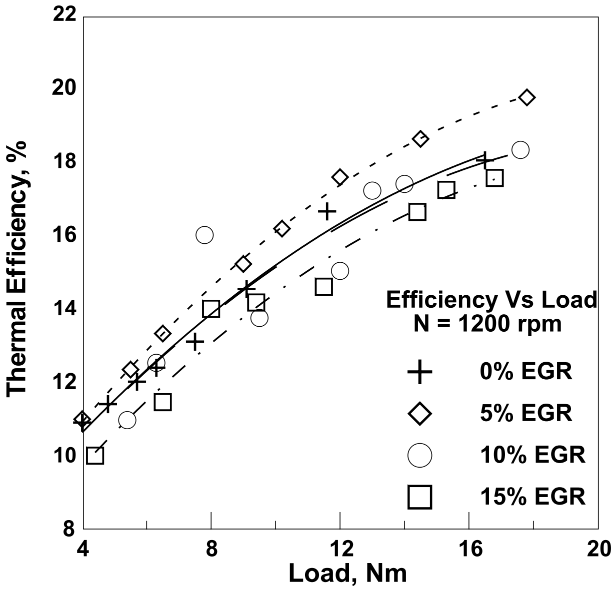

Fig. 5. Effect of load on thermal efficiency, at $N = 1200$ rpm.

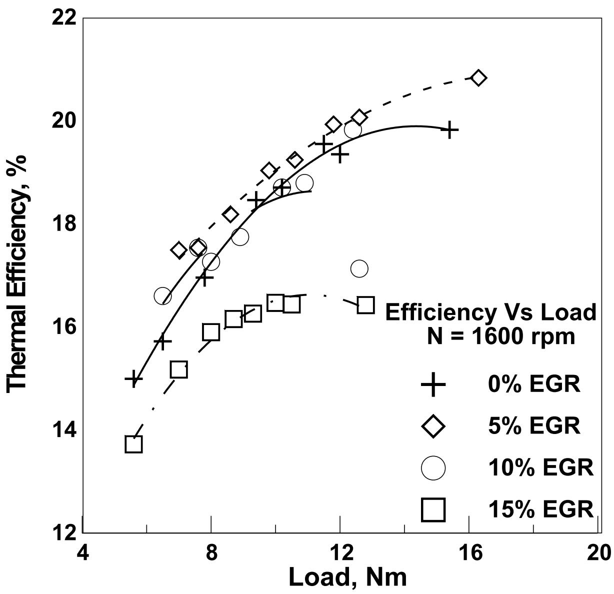

Fig. 6. Effect of load on thermal efficiency, at $N = 1600$ rpm.

dissociation of CO_2 to form free radicals and has been shown to be of minor effect. However, this effect may have caused the slight increase in thermal efficiency, especially at the small EGR ratio of 5%. The thermal efficiency has decreased with any further increase of EGR ratio above 5%. The thermal efficiency was a minimum for 15% EGR ratio at the two engine speeds of 1200 and 1600 rpm. As shown above, this may be due to the dilution effect of the EGR used, as more exhaust gases are present in the combustion chamber with reduced oxygen fraction.

5.2. Pressure rise rate

Figs. 7 and 8 show the effect of load on combustion noise for different EGR ratios at two engine speeds of 1200 and 1600 rpm respectively. It may be seen that the combustion noise for the dual fuel engine generally increases when the load increases. 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 methane may then cause an increase in the ignition delay period of pilot Diesel fuel, which then auto-ignites and starts burning the gaseous fuel at a higher rate of pressure rise.

This has been shown by previous work [15] on a dual fuel engine where natural gas was admitted in the inlet air manifold. It has been shown that the ignition delay of the pilot Diesel fuel was significantly increased by the presence of natural gas. The data shows that the presence of 2% methane in the intake air doubles the ignition delay of the Diesel fuel. This increase in delay period is due partly to the change in specific heat of the compressed mixture that resulted in lowering the compression temperature. The other reason 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. [15]. With the increase in load in the present engine, the amount of gas increased, and hence, these two results may affect the ignition delay.

However, when the EGR ratio is increased from 0% to 15%, the pressure rise rate shows a decrease at all loads. The decrease in maximum pressure rise rate with increasing EGR may be

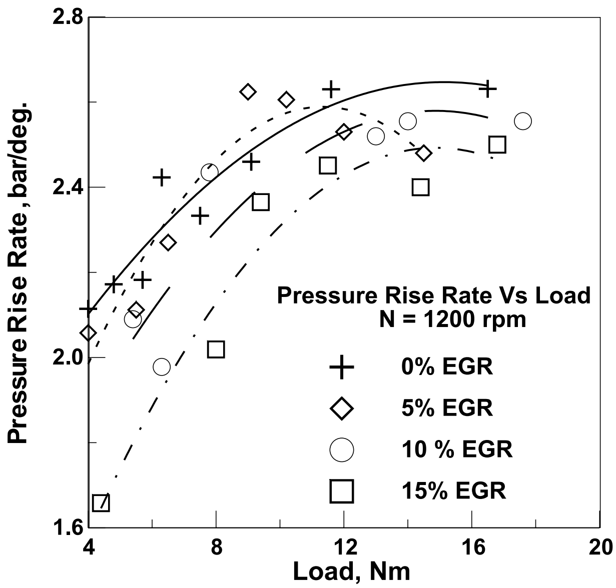

Fig. 7. Effect of load on maximum pressure rise rate, $N = 1200$ rpm.

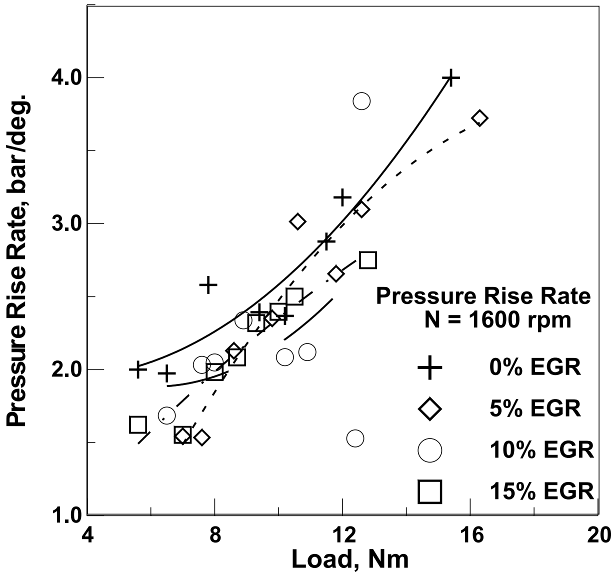

Fig. 8. Effect of load on maximum pressure rise rate, $N = 1600$ rpm.

postulated to be due to the reduction in the peak heat release rate when CO_2 replaces oxygen [13]. The increase in the EGR ratio has a positive effect in reducing the NO_x emission in the exhaust gases, as has been shown by many references, e.g. [13]. This was mainly due to the lower oxygen available for combustion associated with the EGR.

The practical use of EGR, therefore, would be more beneficial for the dual fuel engine, as it reduces the formation of the pollutant NO_x as well the noise generated from combustion. The full benefit of EGR use would be when the thermal efficiency increases slightly (e.g. at the low amount of 5% EGR) and both NO_x and combustion noise decrease.

6. Hot versus cold EGR

The effect of using hot EGR against cold EGR is depicted in Fig. 9 for an engine speed of 1600 rpm and for EGR ratios of 5%, 10% and 15%. The hot EGR condition has been achieved when the EGR piping was thermally insulated to allow for higher gas temperature at the engine inlet. This increased the recycled gase's temperature from about 30 °C to about 55 °C. Fig. 9 shows that the maximum pressure rise rate has increased when using hot EGR as compared to cold EGR. This effect is repeated at all amounts of EGR, used as may be seen in Fig. 9a–c. It has been shown by Ref. [13] that using hot EGR in a Diesel engine has resulted in advancing the whole of the combustion process, which may occur earlier in the compression stroke and cause the maximum pressure rise rate to increase.

The increase in the temperature of the EGR gases also causes the combustion temperature to increase, as well as causing the combustion gases to spent longer periods at these higher temperatures, which leads to an increase in the formation of both NO_x and particulate emissions

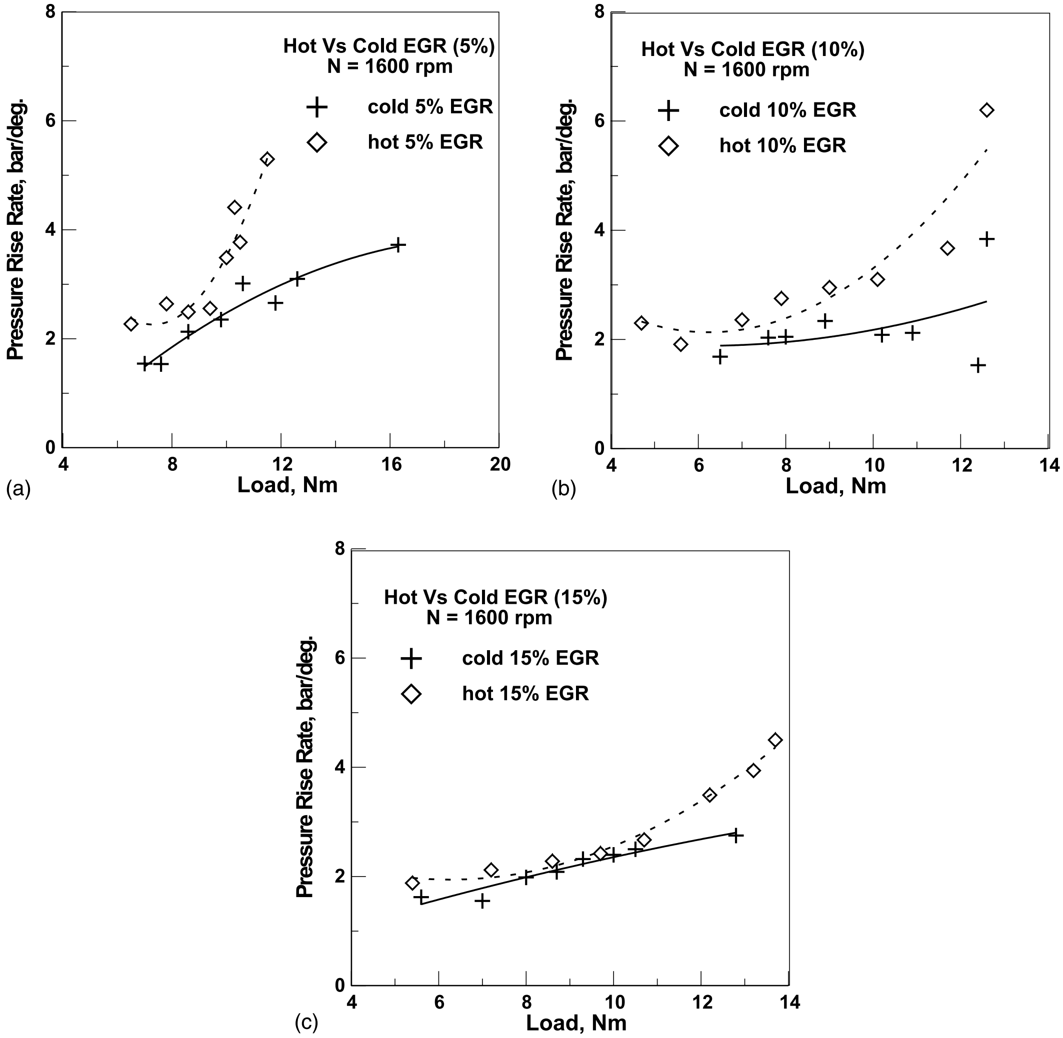

Fig. 9. Effect of load on maximum pressure rise rate for hot and cold EGR.

[7,13]. However, it has been shown [7] that the thermal efficiency has slightly increased when hot EGR is used instead of cold EGR. This was attributed to the possible increased combustion velocity arising from a higher intake charge temperature with hot EGR. In practice, the choice between cooled EGR to reduce NO_x and combustion noise and hot EGR to improve thermal efficiency will have to be made properly to suit specific demands.

7. Effect of inlet pressure

The effect of intake charge pressure on maximum pressure rise rate may be seen in Fig. 10. This test was performed at 0% EGR, since EGR gases could not be used for the higher intake charge

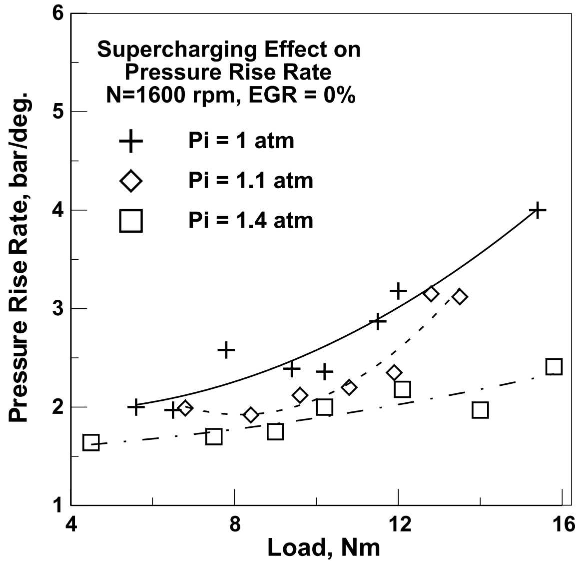

Fig. 10. Supercharging effect on maximum pressure rise rate, EGR = 0%.

pressure. The test is performed at 1600 rpm engine speed and a compression ratio of 22. It may be seen from the figure that increasing the intake charge pressure from 1 to 1.4 atm has a positive effect on reducing the maximum pressure rate at all loads. The decreased maximum pressure rise rate with supercharging may be attributed to the increase in maximum combustion pressure and temperature, which may have decreased the ignition delay period [12]. This decrease in combustion noise with higher intake pressure would make supercharging of dual fuel engines more favorable to reduce the noise pollution from such engines.

8. Effect of compression ratio

The effect of compression ratio on maximum pressure rise rate may be seen in Fig. 11. The test has been performed at an engine speed of 1600 rpm, at two compression ratios, 19 and 22, and for different cold EGR ratios. It may be seen that for all EGR ratios used, the lowered compression ratio is always accompanied by a higher maximum rate of pressure rise at all loads. The maximum pressure rise rate is greatly affected by the compression ratio of the engine, as may be seen from the figure. The lowered compression ratio is associated with lower combustion pressures and temperatures, which may increase the ignition delay period of the pilot Diesel fuel, and this, in turn, increases the pressure rise rate. This was an expected disadvantage for reduced compression ratio of the engine, as well as the reduced thermal efficiency of the engine. This has been shown before for engines using pure Diesel fuel by Refs. [12,16]. The reduction of compression ratio has caused the maximum pressure and temperature to drop and, hence, the ignition delay period to increase [12], the maximum rate of heat release to increase and, finally, the pressure rise rate to increase [16].

It may also be seen from Fig. 11 that for the lower compression ratio of 19, the effect of EGR has a similar effect to that for the higher compression ratio of 22. This is shown by the reduced

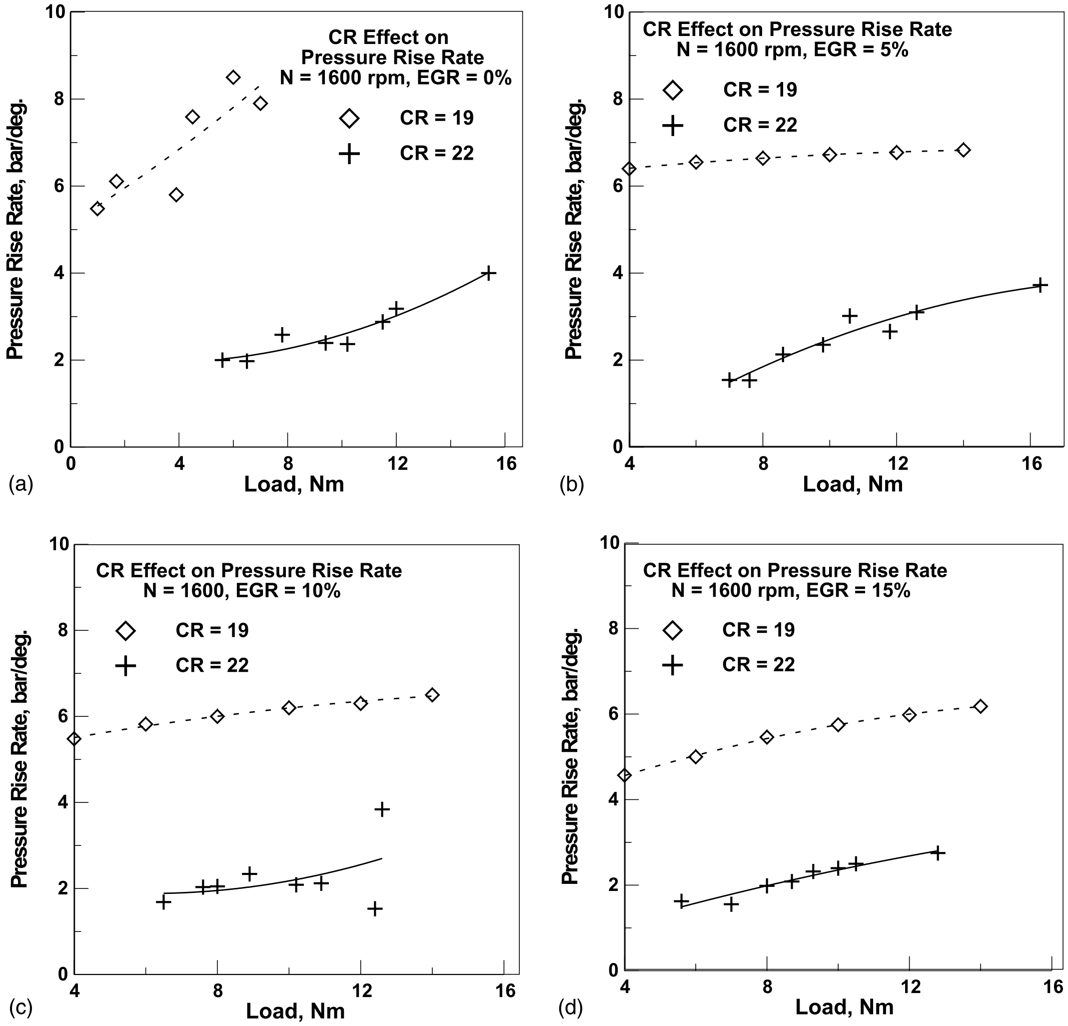

Fig. 11. Effect of load on maximum pressure rise rate for different compression ratios.

pressure rise rate with increase in EGR ratio from 0% to 15%. However, the increase in combustion noise due to reduced compression ratio is lower for higher EGR ratios. This may be seen by estimating the difference between the two compressions ratio data for different EGR in Fig. 11a–d. Fig. 11a shows the highest increase in noise when the compression ratio is lowered, while Fig. 11d shows the lowest increase in noise when the compression ratio is lowered.

9. Conclusions

Combustion noise and thermal efficiency data are presented in this study for a dual fuel engine at different EGR ratios, engine speeds, loads, temperatures of EGR and compression ratios. The combustion noise is represented by the maximum rate of pressure rise during combustion. From the experiments and results presented here, the following conclusions may be drawn:

1. The use of EGR at the low ratio of 5% has a positive effect on increasing the thermal efficiency. However, increasing the EGR has caused the thermal efficiency to drop.
2. The combustion noise decreased with increasing the engine speed for the dual fuel engine. Also, at all engine speeds, the dual fuel engine produced a lower pressure rise rate ($dP/d\theta$) when the EGR is increased.
3. At constant engine speed, both of 1200 and 1600 rpm, increasing the load increases the thermal efficiency for any EGR ratio. Increasing the EGR ratio causes the thermal efficiency to increase, up to 5% EGR, then to decrease at 10% and 15% EGR.
4. At constant engine speed, both of 1200 and 1600 rpm, increasing the load caused the maximum pressure rise to increase. Increasing the EGR ratio causes the maximum pressure rise to decrease at almost all loads.
5. The use of a low EGR ratio of 5% may be favorable in terms of improved thermal efficiency, reduced combustion noise and reduced NO_x emission.
6. Hot EGR has resulted in increased maximum pressure rise rate at all loads and at all EGR ratios used as compared with cooled EGR.
7. The increase in intake charge pressure, as the case of supercharging, has a positive effect in decreasing the combustion noise.
8. When the compression ratio has decreased for the dual fuel engine used, the combustion noise significantly increased at all loads and at all EGR ratios.

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