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Pressure–time characteristics in diesel engine fueled with natural gas

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Abstract

Combustion pressure data are measured and presented for a dual fuel engine running on dual fuel of diesel and compressed natural gas, and compared to the diesel engine case. The maximum pressure rise rate during combustion is presented as a measure of combustion noise. Experimental investigation on diesel and dual fuel engines revealed the noise generated from combustion in both cases. A Ricardo E6 diesel version engine is converted to run on dual fuel of diesel and compressed natural gas and is used throughout the work. The engine is fully computerized and the cylinder pressure data, crank angle data are stored in a PC for off-line analysis. The effect of engine speeds, loads, pilot injection angle, and pilot fuel quantity on combustion noise is examined for both diesel and dual engine. Maximum pressure rise rate and some samples of ensemble averaged pressure–crank angle data are presented in the present work. The combustion noise, generally, is found to increase for the dual fuel engine case as compared to the diesel engine case. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Diesel engine; Natural gas fuel; Pressure–rise rate; Noise

1. Introduction

The availability of methane and/or natural gas fuels has lead to a worldwide spread of internal combustion engines running on the dual fuel concept. Gaseous fuels also promise to be suitable for 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.

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Therefore it is more economical and of environmental advantage to use natural gas in diesel engines which use the dual fuel concept. There have been many published works on the use of natural gas in dual fuel engines from the combustion duration and ignition delay point of view e.g. [1,2], performance and emissions point of view, e.g. [3–6]. Thermal loading and temperature distribution have also been studied for dual engines e.g. [7]. However, one important pollutant is not receiving attention, that is the combustion noise.

Noise is a pollutant by the combustion process that may have 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, [8].

The diesel engine is known to produce much more noise than that produced by the 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 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 in relating the diesel engine combustion noise to the engine operating and design parameters. However, the combustion noise data for the dual fuel engine that utilizes diesel as pilot fuel and gaseous fuel is lacking.

In the present study an attempt is made to relate the combustion noise to the operating parameters for the dual fuel engine as compared to a 100% diesel case. The pressure rise rate is measured and analyzed at different engine loads, engine crankshaft speeds, pilot injection angle, and different pilot mass quantity. The noise data is also compared, at the same conditions, with the diesel engine noise.

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 MkV com-

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	21.07
Maximum power (kW)	9, naturally aspirated
Maximum speed (rpm)	3000
Injection timing	varied 20–45° BTDC

pression 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 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 volts. 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 micro processor-based fuel system, Compuflow System. The gaseous fuel flow rate is measured by using an orifice meter connected to electronic partial pressure transducer that is connected to a digital pressure meter. 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: cylinder pressure data, crank angle degrees signal, liquid and gaseous fuel flow rate data, 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.

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 shape channel and the output is fed into the 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 offline analysis. A computer program is written to find the pressure rise rate data at all cycle points from mid compression stroke to mid exhaust 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 carried out after running the engine for some time until it reaches steady state and the oil temperature is at 50°C±5, and cooling water temperature is at 70°C±5.

Data are presented as pressure rise rate in bar/degrees for the 100% diesel and dual fuel (diesel and methane) for the following operating parameters:

1. The engine speed, varying from 900 to 2000 rpm
2. The engine load, varying from 4 to 23 Nm
3. The pilot fuel injection timing, varying from 20 to 40° BTDC
4. The pilot diesel fuel mass injected, varying from 0.37 to 0.63 kg/hr

3. Results and discussion

The data presented in this section includes some samples of pressure–time data at different operating conditions and the effect of operating conditions on combustion noise. Those variables include engine speed, engine load, pilot injection timing and pilot fuel mass injected per cycle. A typical pressure time diagram is illustrated in Fig. 1, for pure diesel fuel case at light load and at 1889 rpm and 30° BTDC injection timing. The pressure time data is then analyzed by calculating 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

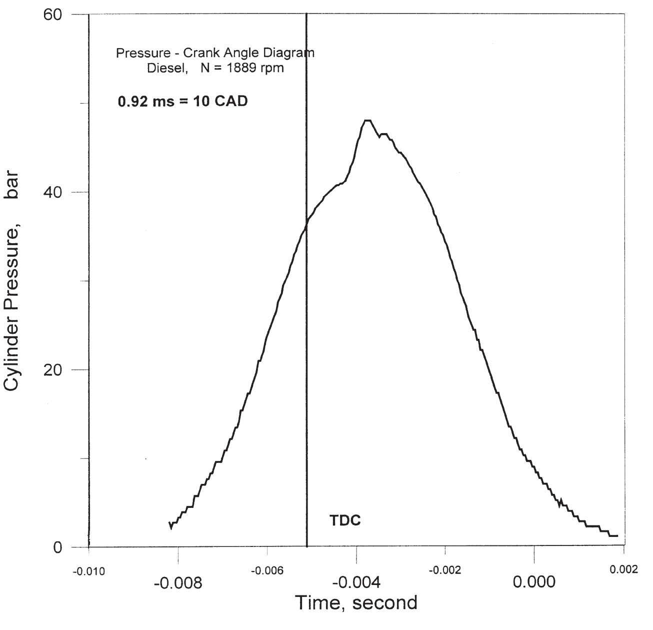

Fig. 1. Typical pressure–time diagram.

time is shown in Fig. 2 for the same pressure data shown in Fig. 1. It can be seen from this figure that the slope of the pressure–time curve increases during compression and the 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, till maximum pressure point. The slope then becomes zero at that point and negative afterwards during expansion stroke. The maximum value of this pressure rise rate data is then taken and recorded, in bars/degrees, at the corresponding conditions.

3.1. Effect of engine speed

The effect of engine speed on combustion noise is depicted in Fig. 3 for diesel and dual fuel cases. Generally, as the engine speed increases, the pressure rise rate ($dP/d\theta$) decreases for the diesel engine case and for dual fuel too. For the diesel engine case, the pressure rise rate drops from about 5.5 bar/°CA at speed of 990 rpm to around 2.93 bar/°CA at 1890 rpm. However, for the dual fuel case the pressure rise rate is higher than that for the diesel case, almost at all engine speeds, and it follows a similar trend to the diesel case. It drops from 6.6 5.5 bar/°CA at 980 rpm to 2.95 5.5 bar/°CA at 1880 rpm.

Figs. 4–6 show a sample pressure–crank angle diagram for three engine speeds of 986, 1522 and 1889 rpm where diesel and dual fuel cases are shown on each graph. It may be seen from these figures that the slope of the pressure–time curve ($dP/d\theta$) is higher for the dual fuel case.

It has also been shown [12] that the combustion noise ($dP/d\theta$) decreased when the engine speed increases. The authors measured the pressure rise rate in the combustion

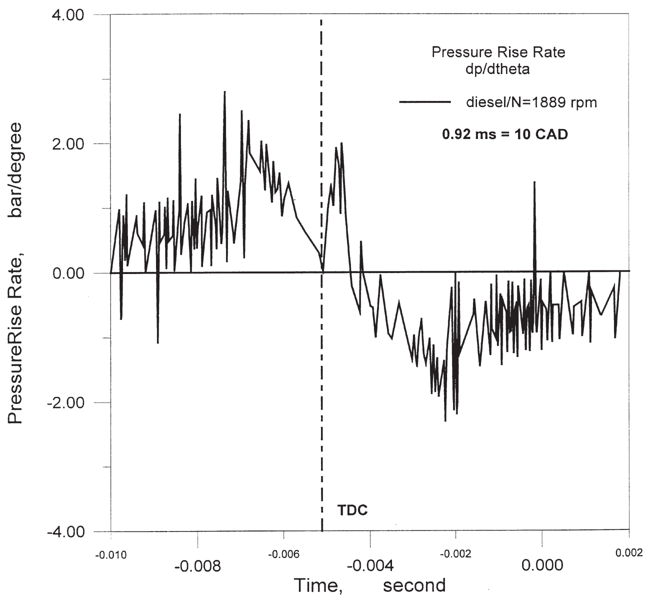

Fig. 2. Typical pressure rise rate–time diagram.

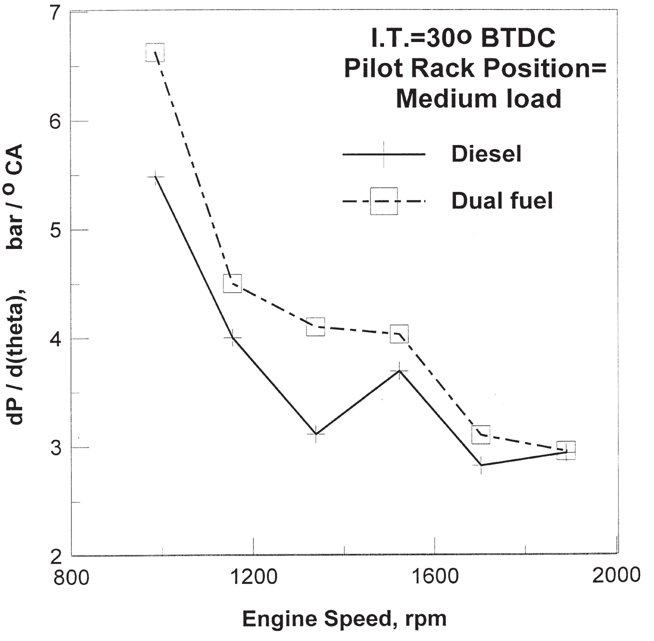

Fig. 3. Effect of engine speed on pressure rise rate for the diesel and dual fuel engines.

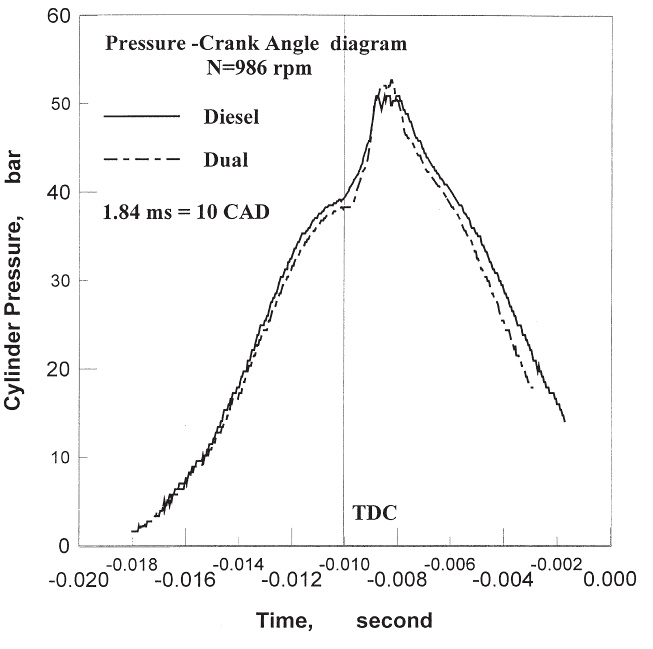

Fig. 4. Pressure–crank diagram for the diesel and dual fuel engines, N=986 rpm.

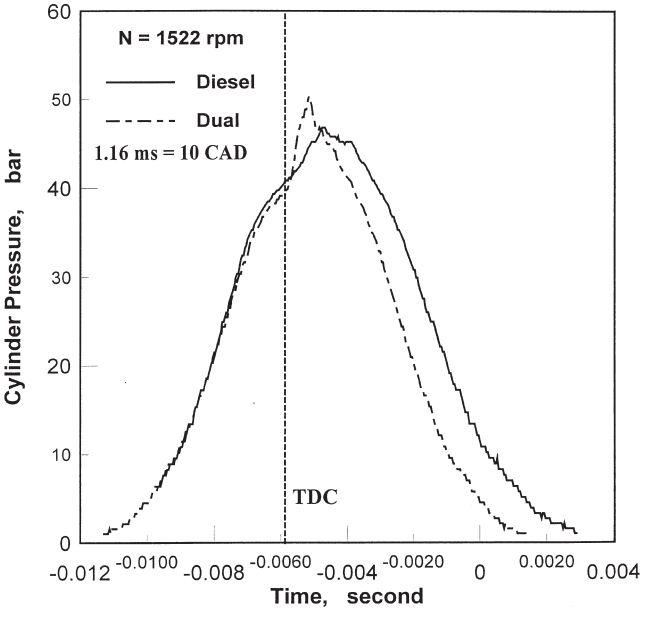

Fig. 5. Pressure–crank diagram for the diesel and dual fuel engines, N=1522 rpm.

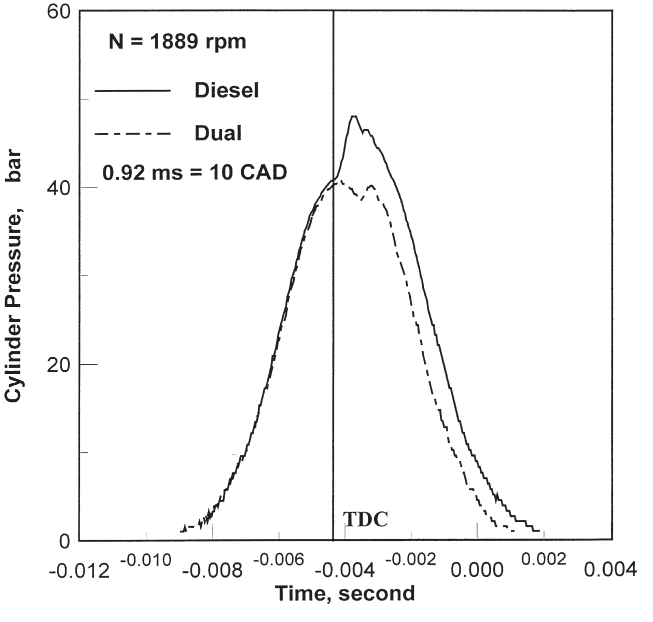

Fig. 6. Pressure–crank diagram for the diesel and dual fuel engines, N=1889 rpm.

chamber of an IDI diesel engine and related it to the sound pressure level (SPL) in decibels (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. As the same time the SPL has increased in 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 the reduction in the maximum rate of heat release.

3.2. Effect of load

The effect of load on combustion noise for the diesel and dual fuel engine is shown in Fig. 7, at an engine speed of 1200 rpm. It may be seen that the pressure rise rate for the diesel engine case increases slightly and when the load increased. However, for the dual fuel case the combustion noise is always higher than that for the diesel fuel case. Combustion noise for dual fuel also increases when the load increases. Combustion noise for the diesel case is around 4 bar/°CA and it only fluctuates slightly around this value. For the dual fuel engine, however, it increased from less than 4 bar/°CA at a load of 4.5 Nm to 15.5 bar/°CA at 18.5 Nm.

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 methane may then cause an increase in the ignition delay period of pilot diesel which then auto-ignites and starts burning the gaseous fuel at a higher rate of pressure rise. This has been shown by previous work [13] on dual

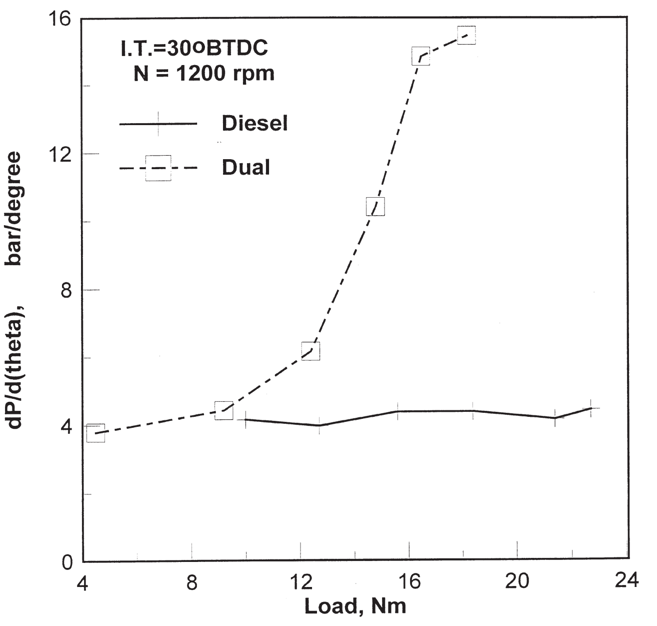

Fig. 7. Effect of engine load on pressure rise rate for the diesel and dual fuel engines.

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 due partly 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 Nielsen et al. With the increase in load in the present engine, the amount of gas increased and hence these two results may affect the ignition delay.

This may also be seen from Fig. 8, which shows the location of the maximum rate of pressure rise wrt, the TDC. It may be seen that for the 100% diesel case the maximum pressure rise rate always occurs well before the TDC (around 20° BTDC) while for the dual fuel case, it occurs after TDC (around 5° ATDC). This may be postulated to increase in ignition delay of the pilot diesel with the increase of load (or increase in methane mass). Figs. 9–11 show the pressure–crank angle diagram of 100% diesel and dual fuel cases at three different loads of 10 Nm, 12.7 Nm and 18.4 Nm respectively. It is shown in these figures that the rate of pressure rise for the dual fuel case (dashed lines) is greater than that for the 100% diesel case (solid

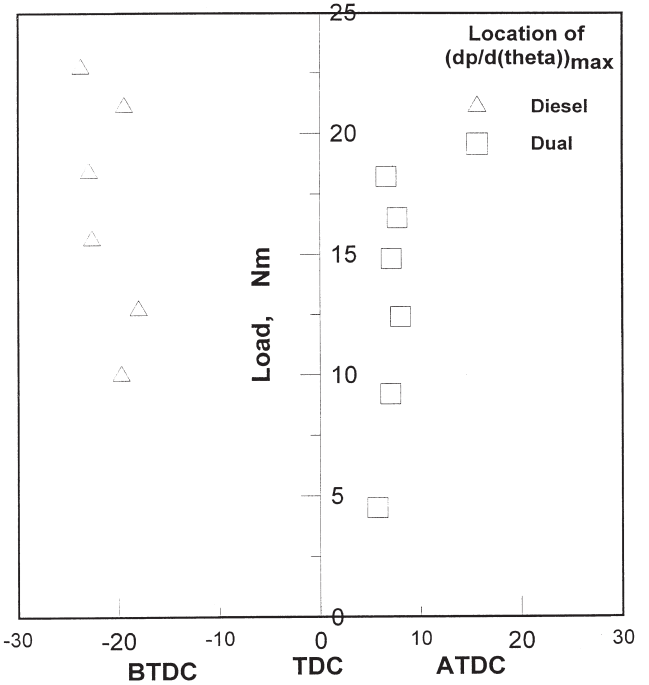

Fig. 8. Effect of engine load on crank angle of maximum pressure rise rate for the diesel and dual fuel engines.

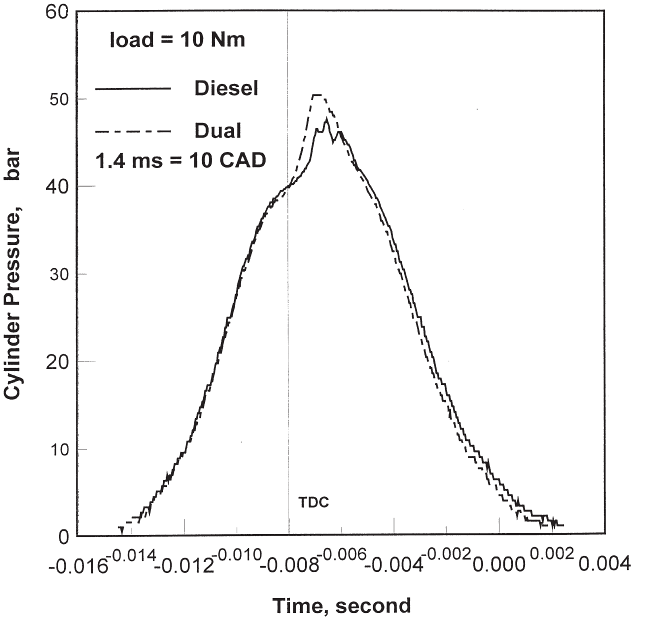

Fig. 9. Pressure–crank diagram for diesel and dual fuel engines, load=10 Nm.

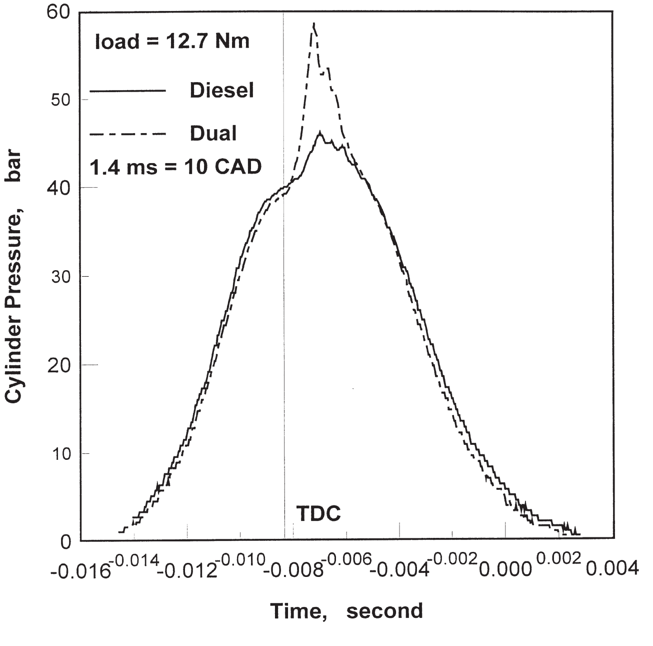

Fig. 10. Pressure–crank diagram for the diesel and dual fuel engines, load=12.7 Nm.

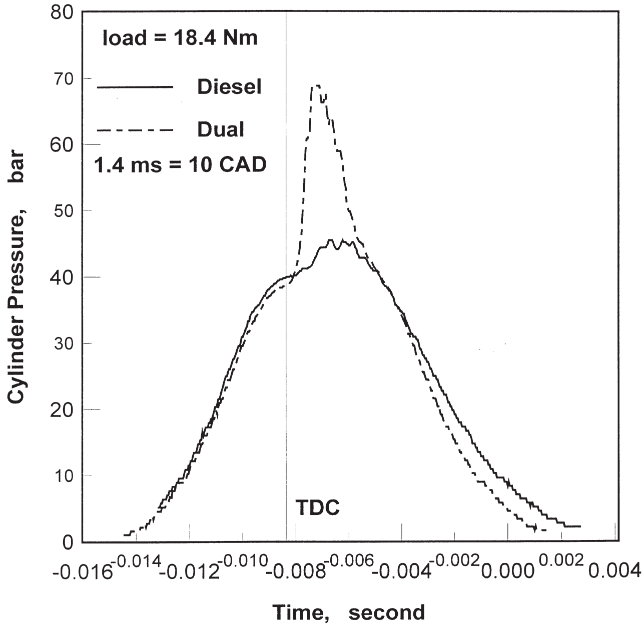

Fig. 11. Pressure–crank diagram for the diesel and dual fuel engines, load=18.4 Nm.

lines), and occurs after the TDC. Also, the maximum pressure is higher for the dual fuel case than that for 100% diesel.

3.3. *Effect of pilot injection timing*

The effect of pilot diesel injection timing on the combustion noise of the dual fuel engine as compared to 100% diesel case is illustrated in Fig. 12. The results shown are at constant engine speed of 1200 rpm. For the 100% diesel case, the results are for constant fuel rack position. For the dual fuel case, the pilot rack position is constant and the amount of methane gas is fixed. The engine produced almost similar torque for the 100% diesel and dual fuel cases. It may be seen that, generally, as the pilot diesel injection advance increases, the combustion noise increases for 100% diesel and dual 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 been also shown [11] 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 in methane gas 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 and be higher than that for the 100% diesel case. This is shown, generally, in Fig. 12 as the pressure rise rate ($dP/d\theta$) for the dual fuel engine is higher than

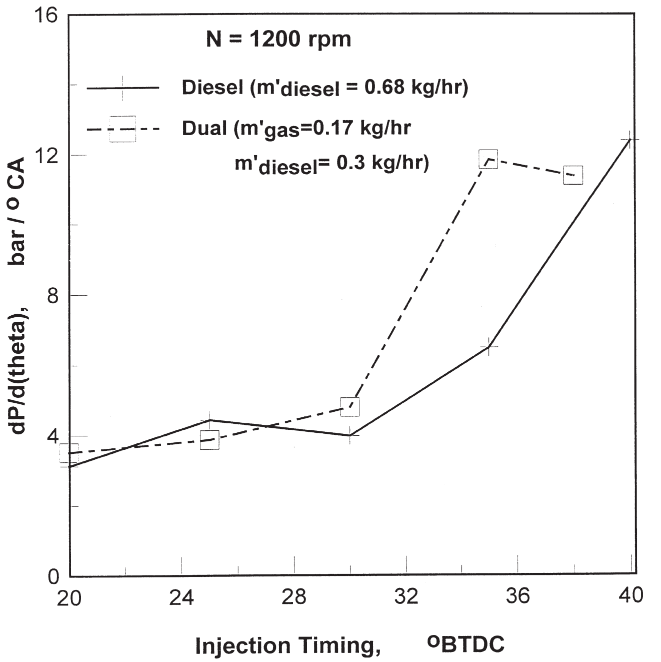

Fig. 12. Effect of pilot fuel injection timing on pressure rise rate for the diesel and dual fuel engine.

for that for the 100% diesel engine. For the late injection of pilot, 20 to 25° BTDC the combustion noise is comparable for diesel and dual fuel cases. However, as the injection advance increases, 25 to 40° BTDC, the dual fuel engine produced a higher rate of pressure rise ($dP/d\theta$). This may be also seen from the samples of individual pressure–crank angle cycles shown in Figs. 13–15 for pilot injection timing of 20, 30 and 40° BTDC respectively. The figures show an increase in the slope of the pressure–crank angle data as the injection advance increased and it is higher for the dual fuel case than when 100% diesel.

3.4. Effect of pilot diesel mass

Fig. 16 shows the effect of pilot diesel mass on the pressure rise rate ($dP/d\theta$) and engine torque for the dual fuel case, while samples of individual pressure–crank angle data are depicted in Fig. 17. The shown results are for a constant engine speed of 1200 rpm, constant pilot injection timing of 30° BTDC, and fixed mass of methane gaseous fuel. It may be seen from Fig. 16 that increasing the pilot diesel fuel mass resulted in an increase in the engine torque. This may be postulated to the increase in the heat released from burning more fuel. The combustion noise ($dP/d\theta$), however, dropped with the increase of pilot mass from around 8.1 bar/°CA at 0.38 kg/hr pilot mass to about 5.12 bar/°CA at 0.52 kg/hr. Pressure rise rate then increases to 7.42 bar/°CA as the pilot fuel mass increases to 0.63 kg/hr. The decrease in the combus-

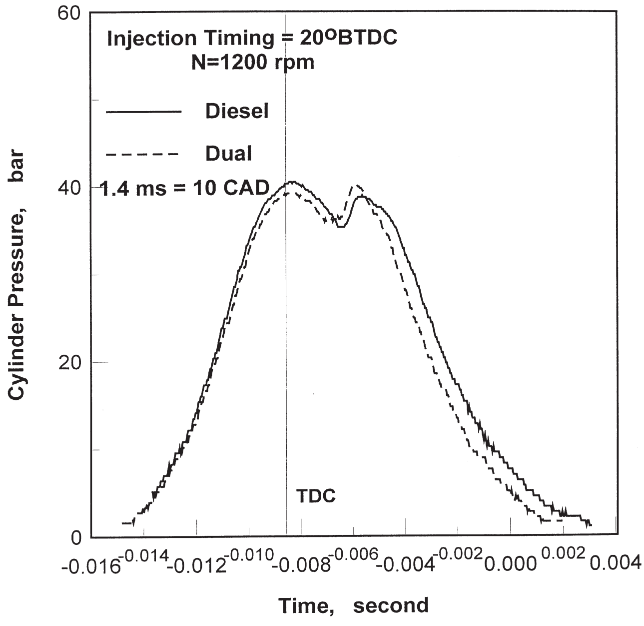

Fig. 13. Pressure–crank diagram for the diesel and dual fuel engines, pilot injection timing=20 degrees before top dead center.

tion noise ($dP/d\theta$) when the pilot fuel mass is first increased may be postulated to the increase in flame volume resulted by the increase in pilot fuel mass which would burn the methane gas smoothly and at a lower rate of combustion. The increase in the initial pilot flame volume may have caused the air/methane mixture to ignite from more mini flames with smaller air/fuel mixture pockets ignited. However, when the pilot fuel mass increased beyond a certain amount, 0.52 kg/hr for this case, the ignition delay period of pilot diesel increased and may have increased the pressure rise rate ($dP/d\theta$) for the methane/air mixture.

Fig. 17 shows a pressure crank angle diagram for different pilot fuel masses of 0.38, 0.44, 0.52 and 0.63 kg/hr. It may be seen from this figure that the maximum pressure and the maximum rate of pressure rise ($dP/d\theta$) is minimum for a pilot fuel mass of 0.52 kg/hr, and it is increased for a lower or higher amount of diesel pilot fuel.

4. Conclusions

Combustion noise data is presented in this study for 100% diesel fuel and a dual fuel engine at different engine speeds, loads, pilot injection timing and different pilot fuel mass. 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:

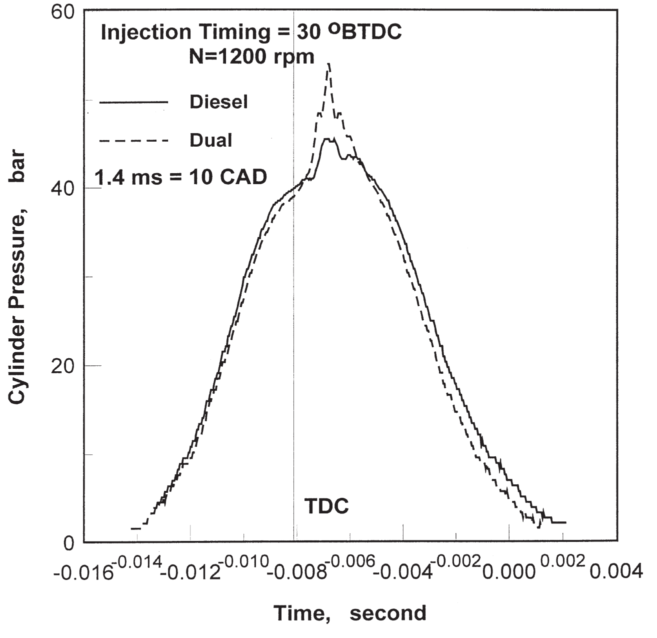

Fig. 14. Pressure–crank diagram for the diesel and dual fuel engines, pilot injection timing=30 degrees before top dead center.

1. The combustion noise decreased with increasing the engine speed for the diesel and the dual fuel engine. Also at all engine speeds the dual fuel engine produced a higher pressure rise rate ($dP/d\theta$) than that for 100% diesel
2. At constant engine speed, increasing the load did not affect the combustion noise much for the diesel engine. However, for the dual fuel engine increasing the load resulted in severe increase in combustion noise, which was much higher than those for the 100% diesel case.
3. The maximum rate of pressure rise for the diesel engine occurred before TDC, while for the dual fuel engine it occurred at a later crank angle, after TDC.
4. For the dual fuel engine, at constant engine speed, the maximum cylinder pressure is higher than that for the 100% diesel case, at all loads.
5. Increase in diesel fuel injection advance results in an increase in the combustion noise. Also it is higher for the dual fuel engine than for 100% diesel.
6. For the dual fuel engine, increasing the mass of pilot fuel mass injected, results in a decrease in combustion noise up to certain value then it starts again to increase. For the engine torque, it is increased with increasing the pilot fuel mass. At a specific pilot fuel mass, the maximum pressure rise rate as well as the maximum pressure were minimum, and they increased at other amounts.
7. Generally the dual fuel engine exhibited higher rate of pressure rise as compared to the 100% diesel engine.

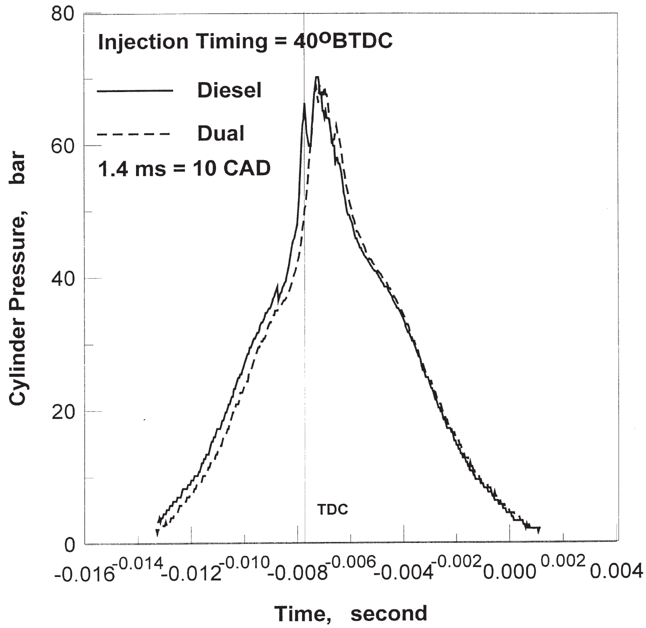

Fig. 15. Pressure–crank diagram for the diesel and dual fuel engines, pilot injection timing=40 degrees before top dead center.

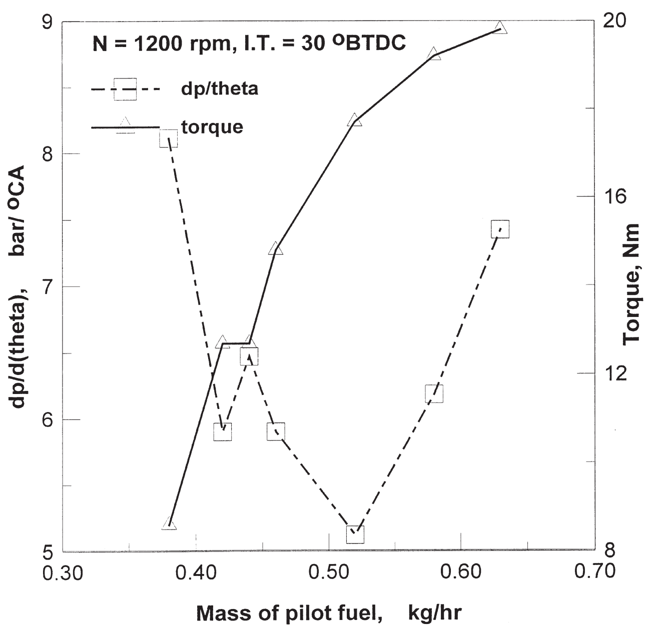

Fig. 16. Effect of pilot fuel mass on pressure rise rate for the dual fuel engine.

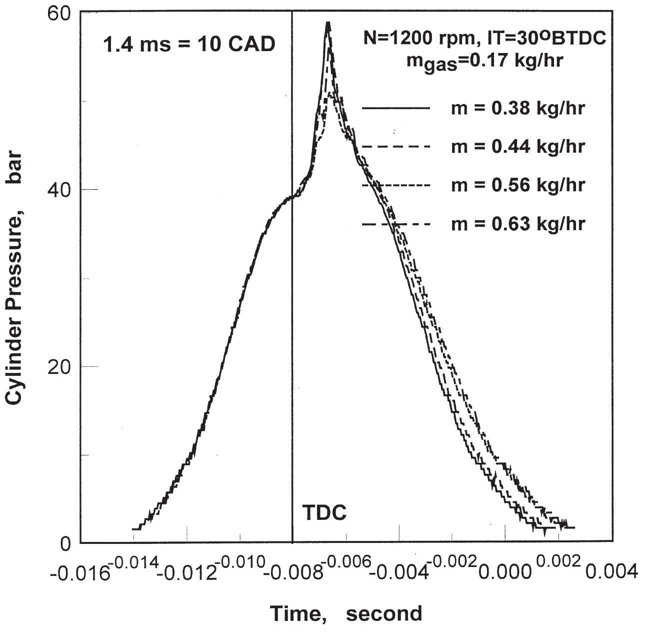

Fig. 17. Pressure–crank diagram for dual fuel engine, at different pilot fuel mass.

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