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Effects of Pilot Oil Injection Timing on Combustion, Covariance and Knocking of a Natural Gas–Diesel Duel-Fuel Low-Speed Engine

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ABSTRACT

Dual-fuel engines, which are powered by natural gas while using a small amount of diesel for ignition, have become an attractive option in the marine sector due to their fuel flexibility and relatively good emission characteristics. Altering the fuel injection timing can change the combustion state of natural gas in the cylinder, which in turn affects engine stability and leads to engine knocking.
In this study, the effects of different pilot oil injection timings on the combustion stability of a marine low-speed natural gas dual-fuel engine with a pre-combustion chamber are evaluated in terms of the pressure rise, covariance of Pmax and IMEP, combustion phase, and knocking. It is found that the maximum cylinder pressure and pressure rise rate increase with an advance in the pilot oil injection time. After the natural gas enters the combustion chamber, it undergoes a process of mixing with air in the combustion chamber, and earlier pilot oil injection leads to an increase in the ignition delay period and shortens the combustion duration of the engine. Moreover, it is found that earlier pilot oil injection times result in an increase in engine IMEP and Pmax cycle fluctuations, and engine knocking also undergoes an increase when the pilot oil injection time is advanced. Hence, an appropriate pilot oil injection time should be considered in the process of optimising engine performance.

Keywords: Duel fuel, Two stroke engine, LNG, Knocking

INTRODUCTION

In the context of rapid scientific and technological development, the internal combustion engine stands out among the many available power sources for its excellent economy and mobility []. However, due to increasingly stringent regulations on emissions and its high fuel consumption, it is inevitable that internal combustion engine fuels will move in the direction of renewable, low-carbon alternatives []. Natural gas has a higher calorific value than diesel, with excellent anti-knockout properties [], and enables more efficient combustion at high compression ratios and lower CO2 emissions []. It is widely used in ships as the main type of fuel [].

Natural gas engines can be divided into spark-ignited and diesel-ignited dual-fuel types, depending on the ignition method []. Spark ignition is widely used in the automotive industry, due to its good starting performance and convenient system layout []. However, pre-combustion chamber ignition is typically used in this mode in large-bore marine engines, due to the low spark plug ignition energy [] []. Natural gas engines can also be divided into pre-mixed and direct injection engines depending on the fuel supply method []. Pre-mixed dual-fuel engines are favoured by shipowners, as they generally have lower NOx emissions and can meet the TIII emission regulations without additional after-treatment, although due to the spontaneous combustion of unburnt end gases (i.e. natural gas-air mixtures) in front of the flame during the premix combustion process, multipoint combustion occurs and leads to engine knocking []. The extreme exothermic nature of end-gas auto-ignition generates strong localised overpressure and consequent pressure oscillations, which can cause damage to the engine block, thus imposing limitations on the commissioning of pre-blended dual-fuel engines []. The huge impact force on the piston caused by knocking may even be transmitted to the crankshaft through the piston rod, resulting in abnormal wear of the crankshaft during engine operation and affecting the safety of engine operation.

The use of pilot oil injection always affects the combustion process in the cylinder, and is also an important factor in the intensity of engine knocking [][]. Currently, there are two main types of pilot oil injection: single injection and multiple injection. Hydrocarbon (HC) emissions and cyclic variations of the engine during single injection are lower than in a multiple injection system, meaning that the multiple injection method has not become popular []. In a single pilot oil injection test, advancing the pilot oil injection timing can improve the thermal efficiency of a diesel engine under high load conditions by up to 43% over a conventional natural gas engine []. It has also been reported that the advance lead fuel injection angle is very limited due to the risk of strong knocking, excessive peak pressure and a high peak pressure rise rate (PPRR). Singh et al. [] showed that early priming of the fuel injection could make a natural gas engine knocking under high engine load conditions. Liu et al. [] noted that a delayed diesel injection timing start was required to reduce the risk of engine blowout and high PPRR under high engine load conditions. In another study [], it was found that priming of the fuel injection timing in advance led to a more adequate mixing of diesel and natural gas, which promoted the generation of activated free radicals in the combustion chamber and the combustion intensity, reduced the combustion duration, and reduced soot, CO and HC emissions. Wang et al. [] found that the pilot oil injection timing had a significant effect on the combustion process of the engine, including the combustion stages of pilot diesel and natural gas, and also determined both the thermal efficiency of the engine and the level of exhaust gas emissions.

Although a large number of studies have been carried out by scholars on the effects of pilot oil injection timing on engine combustion, these have mostly focused on small and medium-sized four-stroke engines. However, the gas sweeping method and natural gas injection position in marine low-speed engines are very different from those of four-stroke engines. In this paper, the effects of the pilot oil injection timing on engine combustion characteristics are investigated for a marine low-speed natural gas engine. The results of this study of the effects of different pilot injection timing on engine combustion and knocking provide a reference for the performance optimisation of natural gas dual-fuel engines.

TEST APPARATUS AND TEST METHODS

INTRODUCTION TO THE TEST SETUP

Tests were carried out with a marine low-speed two-stroke natural gas engine. In this type of engine, a natural gas premixing method is adopted: when the natural gas is running at a certain angle after the piston runs to bottom dead centre, the gas injection valve above the scavenge air port is opened so that the gas enters the cylinder and mixes with the air, and the pilot oil is injected into the cylinder to ignite the mixed natural gas before top dead centre. The effects of different pilot oil injection times on combustion in natural gas engines was investigated by adjusting the pilot oil injection time. Since 75% of the rated power of a marine engine is the usual power, the engine was kept running at 75% of the rated load during the test, and the duration timing of the pilot oil injection and the engine load were kept constant while the pilot oil injection was varied. In this study, the engine was run in the propeller characteristics of the mode. The engine parameters are shown in Table 1.

Tab. 1. Engine parameters

Engine type	Two-stroke, water-cooled
Number of cylinders	4
Bore	400 mm
Stroke	2315 mm
Charging	Turbocharged
Compression ratio	12
Firing order	1-3-2-4

The bench arrangement used in this experiment is shown in Fig. 1 below, and a hydrodynamic device was used to control and measure the real-time output power of the engine. Kistler's 6045B cylinder pressure sensor was used to monitor the changes in engine cylinder pressure. An angle encoder was used to acquire the engine angle signal for transmission to the AVL combustion analyser, and the signal recording trigger was set to 0.1° in the combustion analyser. In total, 3,600 sets of data were recorded for each cycle of the engine, which ensured that the instantaneous changes in the monitored data could be effectively monitored. The pressure of the natural gas in the engine and the safety of the system were controlled by a set of natural gas valve assemblies. Two natural gas injection valves mounted above the sweep port were used to control the starting and stopping of the natural gas injection moment. In the test, the pilot oil timing was controlled by changing the moment at which the actuation current was applied to the pilot oil injection valve.

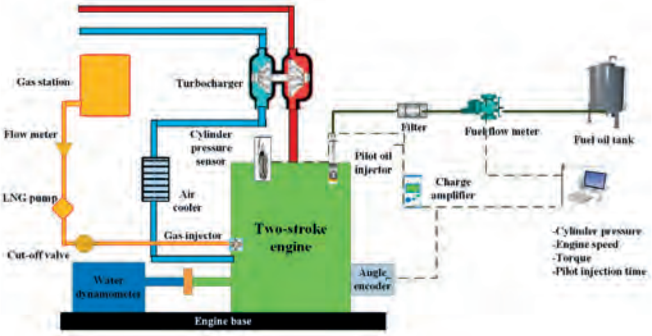

Fig. 1. Schematic diagram of the experimental setup

DATA PROCESSING METHODS

Calculation of cyclic volatility

In this study, the cyclic fluctuation Coefficient of Variation (COV) of the maximum value of the engine in-cylinder pressure Pmax and IMEP data for 100 cycles of engine operation was taken to represent the combustion stability. The formulae used for this calculation are shown below:

$$\mathrm{COV}(\%) = \frac{\sigma}{\mu} * 100 \tag{1}$$

$$(\sigma) = \sqrt{\frac{\sum_{i=1}^{n}(\mu i - \bar{\mu})}{n}} \tag{2}$$

where σ denotes the standard deviation of 100 cycles, and

$$(\bar{\mu}) = \frac{\sum_{i=1}^{n} \mu i}{n} \tag{3}$$

where $\bar{\mu}$ represents the average of 100 cycles

Calculation of burst intensity

In order to represent the burst combustion characteristics of the cylinder pressure signal more intuitively, the maximum pressure amplitude of oscillation (MAPO) was chosen as the burst strength parameter characterising the cylinder pressure signal, in order to assess the burst strength of the cylinder pressure signal.

$$\mathrm{MAPO} = \max(|\hat{p}|_{\theta 0}^{\theta 0+\xi}) \tag{4}$$

where

θ_0 is the crankshaft angle corresponding to the cylinder pressure signal analysis window

ξ is the width of the analysis window

$\hat{p}$ is the filtered cylinder pressure

TEST RESULTS AND ANALYSES

EFFECTS OF PILOT OIL TIMING ON CYLINDER PRESSURE

Fig. 2 shows the in-cylinder pressure and pressure rise rate at 75% of the rated load of the engine at different pilot oil injection angles. The results show that the moment of pilot oil injection has a significant effect on the combustion process of the natural gas engine. With an advancement in the pilot oil injection time, the pressure in the engine combustion chamber increases to some extent, and the angle at which the cylinder pressure reaches its maximum value is advanced. The main reason for this is that under the same natural gas injection conditions, in the premixed combustion process, the earlier ignition fuel timing will form an ignition source earlier in the combustion chamber, which will cause the gas in the cylinder to start to burn before the piston travels to top dead centre, resulting in an increase in the maximum pressure in the engine cylinder. As shown in Fig. 2(a), the pilot oil injection time was advanced from 4° to 12° in front of top dead centre. The maximum pressure increased by about 30 bar, which was also conducive to an improvement in the thermal efficiency of the engine. The earlier in-cylinder combustion process was accompanied by continuous contraction in the volume of the combustion chamber, leading to an increase in the rate of cylinder pressure rise. As shown in Fig. 2(b), the maximum in-cylinder pressure rise rate increases by 5% at the time when the time of the pilot oil injection is advanced from 4° before top dead centre to 12°. The angle at which the maximum rate of pressure rise occurs is also advanced from 7° after top dead centre to 4° before top dead centre.

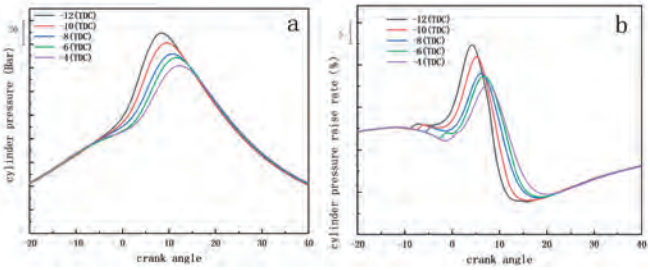

Fig. 2. Variation in cylinder pressure and pressure raise rate for different pilot oil injection angles

EFFECT OF PILOT OIL INJECTION TIMING ON IGNITION DELAY AND COMBUSTION DURATION

Fig. 3 shows the variation in ignition delay and ignition duration for different pilot oil injection times. It can be clearly seen that the ignition delay and combustion duration change significantly with an advance in the pilot oil injection time. In this study, the time interval AI05 between the moment of pilot oil injection and the time when the combustion heat release rate was 5% of the total heat release rate is defined as the ignition delay period, and the time between AI05 and the time at which the combustion heat release rate is 90% of the total heat release rate is defined as the combustion duration. From Fig. 3, it can be observed that with an advance in the ignition fuel injection timing, the engine ignition delay increases, mainly due to the injection of pilot oil into the piston before top dead centre. An earlier pilot oil injection timing will prevent the natural gas and the air being fully mixed. Moreover, the temperature and pressure in the cylinder increase at the same time when the pilot oil is injected into the cylinder earlier, so the ignition delay becomes shorter as injection of the pilot oil becomes closer to top dead centre. The ignition delay can be reduced by injecting the pilot oil closer to top dead centre, but the combustion duration is reduced, due to the intense combustion caused by the high local natural gas concentration for an early pilot oil injection. When the pilot oil is injected 4° before top dead centre, this also accelerates the rate of combustion, due to the uniformly high temperature air-fuel mixture that has been formed, which in turn reduces the duration of fuel combustion.

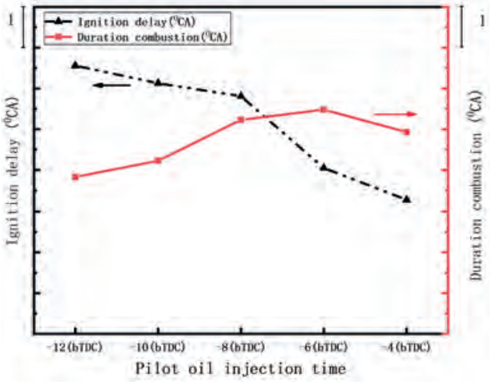

Fig. 3. Variation in ignition delay and duration combustion for different pilot oil injection angles

EFFECT OF PILOT OIL TIMING ON CYCLIC STABILITY

Fig. 4 shows the effects of varying the moment of fuel injection on the maximum in-cylinder burst pressure and IMEP cycle in the engine, under the same engine load conditions. We use COV_PMax and COV_IMEP to characterise the stability of engine combustion. A high value of COV means more fluctuation between each cycle of the engine, which affects the stability of engine combustion and stable power output. A value for COV_IMEP of more than 10% will result in violent engine vibrations in the working process, or even misfiring []. As can be seen from Fig. 4, COV_Pmax rises from 3% to 4.6% and COV_IMEP rises from 0.8% to 1.3% with an advancement in the pilot oil injection time, and both show an increasing trend. The main reason for this is that with a delay in the pilot oil injection, the mixing of natural gas and air is more uniform; this promotes the formation of activated free radicals, enhances the stability of the combustion in the cylinder, and gradually reduces the COV. With an advance in the pilot oil injection timing, the pressure in the cylinder during the pilot oil injection is relatively low, and the diesel oil injected by the pilot oil injection may lead to the phenomenon of wet wall [15]. An earlier pilot oil injection also leads to a longer mixing time for the diesel and natural gas, producing a leaner mixture, which inhibits the formation of an ignition point. The smaller fire core reduces the ignition area and combustion efficiency of the natural gas, thus leading to increasing combustion stability.

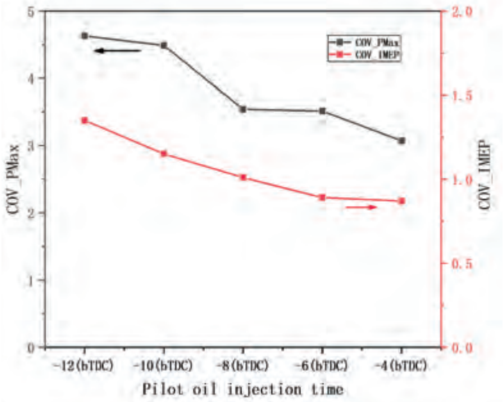

Fig. 4. Variation in COV_PMax and COV_IMEP with different pilot oil injection angles

EFFECT OF PILOT OIL INJECTION TIMING ON THE STRENGTH OF KNOCKING

The cylinder pressure method is the most direct form of knocking detection, as the cylinder pressure signal can directly reflect the combustion of the mixture in the combustion chamber, and this approach has a very high detection accuracy. In order to more clearly show the combustion characteristics of the abnormal pressure signal, the MAPO is selected here as the knocking parameter for the cylinder pressure signal. In order to study the frequency range over which knocking occurs, We first apply a Fourier transform to the cylinder pressure curve, to get the frequency state of the cylinder pressure distribution. Fig. 5(a) shows a graph of the engine cylinder pressure in the frequency domain under stable operation of the engine, and Fig. 5(b) shows the distribution of the cylinder pressure in the frequency domain of the engine under conditions of knocking. Through comparison, we can see that in the event of knocking, the engine cylinder pressure in the frequency range of 1300 Hz partial pressure will undergo a significant increase; we can also assume that the pressure generated in this frequency band is caused by knocking. Hence, for the cylinder pressure filtering calculation, we choose an 800–1600 Hz band pass filter for filtering.

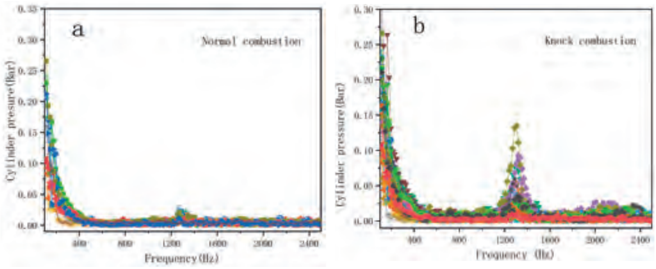

Fig. 5. Variation in cylinder pressure at different frequencies under normal and knocking combustion condition

Fig. 6 shows the filtered fluctuation in cylinder pressure for a natural gas engine in a steady state and in the knocking state. When the MAPO index is used to evaluate these two combustion cycles, we obtain a MAPO value of 1.5 bar for these two cycles when knocking occurs, and a value of 0.1 bar under normal combustion. However, since the phenomenon of knocking occurs randomly in the process of combustion in the engine, it is inaccurate to use the combustion in a given cycle to determine the overall combustion state of the engine. Hence, an average of the MAPO values over 100 cycles was used to evaluate the stability of combustion in the engine in the steady state.

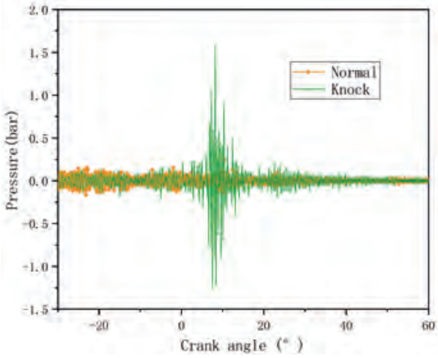

Fig. 6. Variation in cylinder pressures for different crank angles under normal and knocking combustion conditions

The results for the MAPO and an average value over 100 working cycles under varying pilot oil advance angles are shown in Fig. 7. When the pilot oil is injected before 12°CA TDC, the MAPO value over 100 working cycles is the largest, and the average value of the maximum pressure oscillation amplitude of the cylinder pressure signal shows a gradually increasing trend. When the pilot oil advance angle decreases, the average value of MAPO also decreases gradually, and the MAPO value over 100 cycles is also relatively small; in this case, the combustion is also more stable, and the probability of knocking is lower. When the pilot oil advance angle is 12°CA, the average MAPO value is 0.6 bar; when the advance angle is 4°CA, the average MAPO value is 0.45 bar. With a decrease in the pilot oil injection time, the average value of MAPO also decreases gradually. This is because in a natural gas engine, after natural gas has been injected into the cylinder, it mixes with scavenged air. Before the piston moves to TDC, an earlier moment of pilot oil injection will prevent the combustion gas from becoming uniformly mixed after the injection, and the partial over-concentration of combustible gases will create intense combustion caused by the phenomenon of knocking. Hence, with a reduction in the ignition advance angle, the engine cylinder oscillation becomes more violent, and the possibility and intensity of knocking become lower.

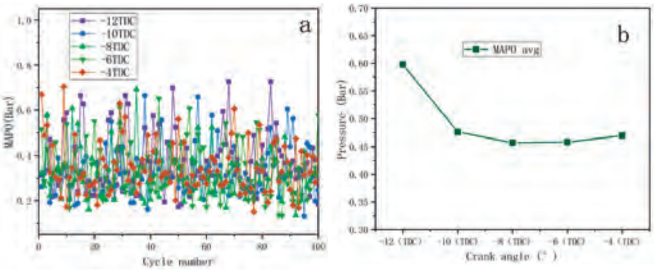

Fig. 7. Variation in MAPO for an engine with different pilot oil injection angles

CONCLUSION

In this paper, we have carried out a study of the effects of pilot oil injection timing on engine combustion on a marine low-speed natural gas dual-fuel engine. These experiments showed that different pilot oil injection timing will have significant impact on a natural gas dual-fuel engine. An appropriate pilot oil injection time should therefore be considered in the process of optimising engine performance. Our results can be summarised as follows:

(1) With an advance in the pilot oil injection time, the maximum in-cylinder pressure of the engine and the pressure rise rate becomes higher. When the pilot oil injection timing is advanced from 4° to 12° from top dead centre, the maximum pressure in the engine cylinder is increased by about 30 bar, and the maximum pressure rise rate in the cylinder is 5%. The ignition delay period increases with an advancement of the pilot oil injection time, while the combustion duration period shows the opposite trend.

(2) As the angle of pilot oil injection is advanced, the temperature and pressure in the cylinder become lower, resulting in a larger ignition delay. At the same time, an advancement in the pilot fuel injection time results in uneven mixing of natural gas and air during ignition, leading to greater combustion fluctuations from cycle to cycle. This creates combustion instability, and causes both COV_Pmax and COV_IMEP to rise over 100 cycles.

(3) We apply 800–1600 Hz band pass filtering to the cylinder pressure to obtain the MAPO indicator used to evaluate the intensity of the knocking. In dual-fuel engines, natural gas is mixed with air through the scavenged air flow when the natural gas and air are not completely mixed, and an earlier pilot oil injection timing will cause the locally over-concentrated mixture of gases to combust violently, resulting in significant knocking of the engine.

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