

Improvement of Performance and Reduction of Exhaust Emissions by Pilot-Fuel-Injection Control in a Lean-Burning Natural-Gas Dual-Fuel Engine

Takuji Ishiyama, Jeongho Kang, Yutaka Ozawa
Kyoto University

Takahiro Sako
Osaka gas Co. Ltd.

Copyright © 2011 Society of Automotive Engineers of Japan, Inc. and Copyright © 2011 SAE International

ABSTRACT

The purpose of this study is to determine a pilot injection control strategy for the improvement of dual-fuel combustion with a lean natural gas/air mixture. Experiments were performed using a single cylinder test engine equipped with a common-rail injection system. The injection pressure, timing and quantity were varied at a fixed overall equivalence ratio of 0.5. The results of single-stage-injection experiments show that middle injection timings (-20 to -10 degATDC) produce low emissions of unburned species, because the pilot-fuel vapor spreads into the natural-gas lean mixture and raises the effective equivalence ratio, which leads to fast flame propagation. Early injection (-35degATDC) is advantageous for low NO_x emission; however, increased emissions of unburned species are barriers. Two-stage pilot injection offers improved thermal efficiency and reduced exhaust emissions when early first-stage injection (-45 to -40degATDC) and moderately early second-stage injection are selected. Analysis of the heat release rate data indicates that the second injection controls the start of heat release, while the first-stage injection affects the overall flame propagation speed. Increased ratio of the first-stage injection quantity is useful for low hydrocarbon (HC) and NO_x emissions with high thermal efficiency.

INTRODUCTION

Dual-fuel operation with the combustion of a lean natural gas/air premixture initiated by ignition of a pilot diesel-fuel spray has potential for high thermal efficiency and low NO_x emission. Natural-gas dual-fuel engines have been investigated as an alternative to heavy duty diesel engines for buses and trucks, and higher thermal efficiency than spark-ignition engines has been achieved [1-3].

A recent application of this combustion method is micro-pilot ignition combustion in stationary

natural-gas engines for cogeneration systems. In the micro-pilot ignition system, a small amount of diesel fuel is injected into a subchamber and ignited to form ignition sources for lean premixtures inside and outside the subchamber. This enables stable combustion of a homogeneous lean premixture with an air excess ratio higher than 2.0, which results in high thermal efficiency with sufficiently low NO_x emission [4,5]. In addition, an open-chamber type dual-fuel engine without a subchamber has also been recently put to practical use [6].

Dual-fuel combustion starts with ignition of a fuel/air mixture formed by pilot-fuel spray. According to a study where an optical engine was used [7], combustion proceeds with flame propagation in the natural gas/air premixture after ignition of the pilot fuel. Knocking with rapid heat release occurs when the equivalence ratio of the premixture exceeds a certain level, which is dependent on the compression condition. In contrast, when the premixture is excessively lean for flame propagation, high emissions of unburned species are observed or misfires occur occasionally [2,3,8].

Application to vehicle engines that are used over a wide range of load and speed requires suppression of unburned species emissions to improve the low and middle load performance. In addition, leaner operation without deterioration of emissions is expected to attain higher thermal efficiency for large stationary engines.

Dual-fuel combustion is a hybrid of pilot-fuel spray combustion and flame propagation of a premixture. Considering the role of pilot-fuel spray as a heat source, the ignition timing, amount of released heat and the spread of burn area have a significant influence on the flame development; therefore, the pilot-fuel injection conditions play an important role. Recently, electrically controlled common-rail type injection systems have been generally used, which

enable flexible control of the injection timing, injection pressure and number of injection pulses, and these systems could be applied to improve dual-fuel combustion.

The effect of the pilot injection conditions on dual-fuel combustion has been investigated. Tomita et al. varied the injection timing over a wide range for a single-cylinder naturally-aspirated engine fuelled with pure methane [9]. Very early injection (-50 degATDC) was demonstrated to improve the NO_x-hydrocarbon (HC) trade-off relation without decreasing thermal efficiency, although knock-free and misfire-free operation was obtained only in a narrow range of equivalence ratio (0.5-0.65).

Krishnan et al. conducted experiments using a single-cylinder supercharged engine with a common-rail injection system and 98% methane fuel [10]. The results indicate that -45 degATDC injection maximizes thermal efficiency with minimum HC and CO emission at full load. They stated that early pilot injection provides many ignition points in the natural-gas mixture, which leads to fast flame propagation.

Aroonsrisopon et al. demonstrated the advantage of two-stage pilot injection at a light load for a naturally aspirated single-cylinder engine [11]. They showed that a large quantity, very early first injection (-50 degATDC) is effective for improvement of performance and reduction of exhaust emissions.

This study aims to determine pilot-injection strategies to improve combustion in dual-fuel operation with a lean natural gas/air premixture. Experiments were performed with various injection conditions for single-stage and two-stage pilot injection using a single-cylinder test engine equipped with a common-rail injection system. The obtained data were analyzed to further understand the combustion processes and determine appropriate injection conditions for lower NO_x and unburned species emissions with high thermal efficiency.

The basic characteristics of dual-fuel operation are first confirmed by varying the total equivalence ratio. The effects of pilot injection pressure and timing are then investigated for the case of single-stage pilot injection at a fixed total equivalence ratio of 0.5, which corresponds to the middle load of the test engine. The heat release rates for dual-fuel and pilot-fuel-only operation are compared to understand the change in the combustion process with pilot injection timing. Finally, two-stage pilot injection data are presented with various timings and quantities of first- and second-stage injection, from which the role of each injection stage is revealed and a strategy for the selection of injection conditions is discussed.

EXPERIMENTAL

The engine used in this study was based on a single-cylinder four-cycle naturally aspirated direct

injection diesel engine, of which the major specifications are listed in Table 1.

Table 1 Specifications of the test engine

Engine type	Direct-injection diesel engine, Single-cylinder, Water-cooled
Bore/Stroke	102/105mm
Displacement	857cm ³
Compression ratio	17.8
Combustion chamber	Toroidal type with a $\phi 56.7$ bowl
Swirl ratio	2.6
Intake charging	Naturally-aspirated, no EGR
Pilot fuel supply	Common-rail system 0.12mm $\times$ 6 holes 140° nozzle (solenoid type)
Main fuel supply	Continuous supply into an intake pipe

To supply pilot fuel, an electrically controlled common-rail injection system was installed in place of the original injection pump and injector. The high-pressure supply pump was driven by an electric motor. Energy consumption of the pump was not included in the calculations of thermal efficiency and the mean effective pressure. The injector was a solenoid-actuated type with a 140° nozzle having six 0.12 mm orifices. JIS No.2 diesel fuel (cetane index 58, sulfur 6 ppm) was used as the pilot fuel. Figure 1 shows the shape of the combustion chamber and the direction of pilot fuel spray. Piston positions for several crank angles are also illustrated for reference.

The main fuel, Japanese 13A natural gas (CH₄ 88 vol%, C₂H₆ 6 vol%, C₃H₈ 4 vol%, C₄H₁₀ 2 vol%), was continuously supplied into the intake pipe 300 mm upstream from the cylinder head. The mass flow rate was measured using a hot-wire flow meter (STEC SEC-4600R). The intake charge temperature was regulated using an electric heater installed in the intake pipe.

All measurements were conducted at thermal steady states of the engine at a fixed speed of 1200 rpm, an inlet cooling water temperature of 80°C, and a lubricating oil temperature of 70°C. The intake charge temperature had a significant influence on the available operating range, especially for early injection timings. Therefore, the temperature was maintained at 40°C, except for those experiments in the early stage of the study, which were carried out

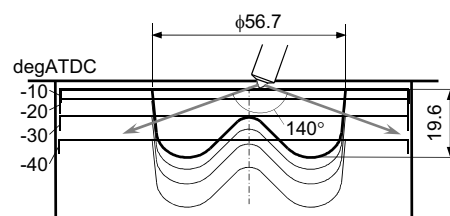


Fig. 1. Combustion chamber and spray direction.

under room temperature conditions.

Smoke emissions were measured using a smoke meter (Zexel DSM-10B). Total hydrocarbon (THC) and CO concentrations were measured with a heated flame ionization detector THC analyzer (Horiba MEXA-1160TFI-H) and a non-dispersive infrared analyzer (R-Science ALTAS12), respectively. NOx emission was measured using a chemiluminescent analyzer (Horiba CLA-510SS). The in-cylinder pressure was measured using a piezoelectric pressure sensor (Kistler 6052A). The average pressure for approximately 20 cycles was used to

calculate the heat release rate.

RESULTS AND DISCUSSION

BASIC CHARACTERISTICS OF DUAL-FUEL OPERATION

Experiments were first performed by varying the total equivalence ratio ϕ with a fixed pilot injection timing θ_i of -10 degATDC and an injection pressure p_i of 80 MPa. The quantities of pilot fuel q_i , were set at 3, 5 and 10 mm³ per cycle, which correspond to 9, 16 and 30% of total input heat at $\phi = 0.5$. The injection durations were 2.0, 2.75 and 5.0 degCA, respectively. For each pilot fuel quantity, the natural gas flow rate was regulated to obtain the target total equivalence ratios.

Figures 2 and 3 show the results for exhaust emissions and performance and include the data for conventional diesel-fuel operation (Diesel operation). $dp/d\theta_{max}$ represents the maximum rise rate of in-cylinder pressure. The combustion efficiency η_c was calculated from the measured concentrations of THC and CO.

THC and CO emission levels were much higher compared with diesel operation. At low equivalence ratios ($\phi < 0.5$), THC and CO increase with a decrease in the pilot fuel quantity q_i , and this tendency has been reported previously [2,3,8]. On the other hand, these emissions are not significantly influenced by q_i for higher ϕ . The combustion efficiency η_c , is almost determined by THC emission level. The brake thermal efficiency η_e and brake mean effective pressure (BMEP) are significantly influenced by the trend of η_c . Therefore, elevation of the combustion efficiency is crucial to improve the thermal efficiency.

NOx emissions were lower than in diesel operation for lower ϕ and increased to high levels for higher ϕ . Smaller q_i is advantageous for lower NOx emission. $dp/d\theta_{max}$ increased with q_i and exceeded the allowable level (0.5 MPa/deg) when q_i was greater than 5 mm³. Smoke emission was below the detectable level for all conditions tested, although the results are not shown here.

Figure 4 shows the effect of ϕ on the heat release rate $dQ/d\theta$, in-cylinder pressure p , and the average in-cylinder temperature T , for the smallest q_i of 3 mm³. The $dQ/d\theta$ curve consists of an initial sharp spike induced by combustion of the pilot fuel, and a following broad peak due to flame propagation of the natural gas/air premixture. In this study, the combustion phase corresponding to the initial peak is referred to as the initial combustion and the phase characterized by the second peak is referred to as the main combustion.

$dQ/d\theta$ of the main combustion increases markedly and the peak position advances when ϕ exceeds

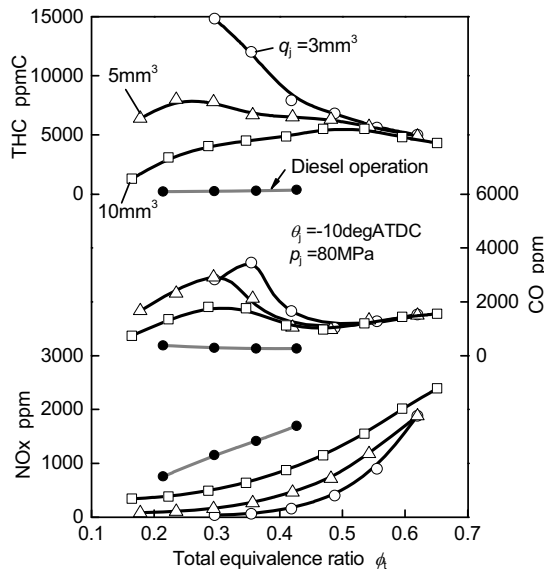


Fig. 2. Exhaust emissions against total equivalence ratio for pilot injection quantities of 3, 5 and 10 mm³/cycle.

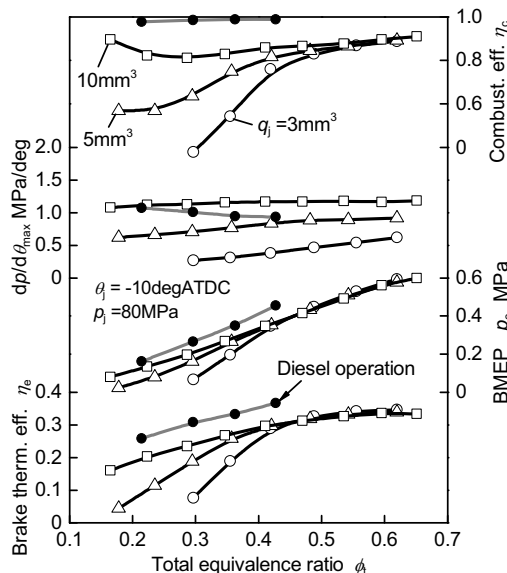


Fig. 3. Performance against total equivalence ratio for pilot injection quantities of 3, 5 and 10 mm³/cycle.

0.42, which means that flame propagation starts to be accelerated beyond this ϕ . This trend was also observed for larger q_i , which corresponds to the THC and CO emissions, which were scarcely affected by the pilot fuel quantity, as shown in Fig. 2.

In the following experiments, ϕ was selected to be 0.5. From the previous results, this selection means that flame propagation is ensured if the injection timing and quantity are not far from those in Figs. 2 and 3.

SINGLE-STAGE PILOT INJECTION

To improve understanding of the combustion process and select suitable injection conditions, experiments were conducted with various injection pressure, timing and quantity in single-stage pilot injection mode at a fixed total equivalence ratio of 0.5.

Selection of injection pressure

Increasing injection pressure is expected to enhance flame propagation and reduce emissions of unburned species due to the spread of pilot fuel vapor in the natural gas/air premixture. However, mixing of the vapor with the premixture tends to be excessive, because the injection quantity is very small, which would cause over-dilution of the pilot fuel vapor and weaken the effect. To determine the optimal injection pressure, experiments were performed at a fixed pilot quantity of 3 mm^3 , and the results are shown in Figs. 5 and 6. Here, COV(IMEP) represents a relative cycle-to-cycle variation of indicated mean effective pressure (IMEP), the root mean square of IMEP divided by the average.

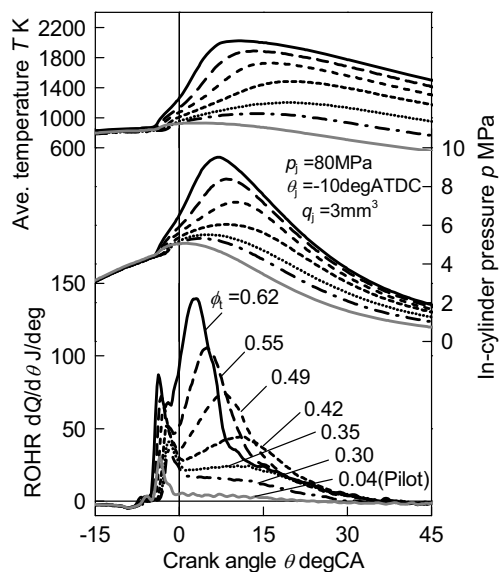


Fig. 4. Effect of total equivalence ratio on heat release rate, in-cylinder pressure and average temperature for a pilot injection quantity of $3 \text{ mm}^3/\text{cycle}$.

COV and THC emission increase as the injection pressure p_i increases at an injection timing θ_i of -20 degATDC, while the tendency is contrary at a later θ_i of 0 degATDC. At the middle injection timing (-10 degATDC), p_i has a weak effect on the performance and emissions.

Figure 6 indicates that the ignition is delayed and the major part of the heat release rate shifts into the expansion stroke for higher p_i in the case of early θ_i (-20 degATDC). On the other hand, for $\theta_i = 0$ degATDC, higher p_i provides slightly higher $dQ/d\theta$ in the main combustion phase. At the middle θ_i (-10 degATDC), p_i has little effect on $dQ/d\theta$ in the main combustion.

To reveal the reason for this tendency, experiments were performed without supplying natural gas. Based on the obtained heat release rates, the influence of injection pressure on mixture formation with pilot spray was estimated, and the results are shown in Fig.

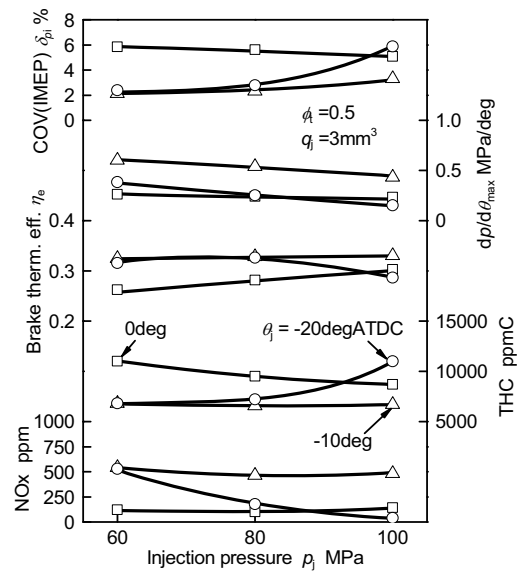


Fig. 5. Effect of injection pressure on performance and exhaust emissions.

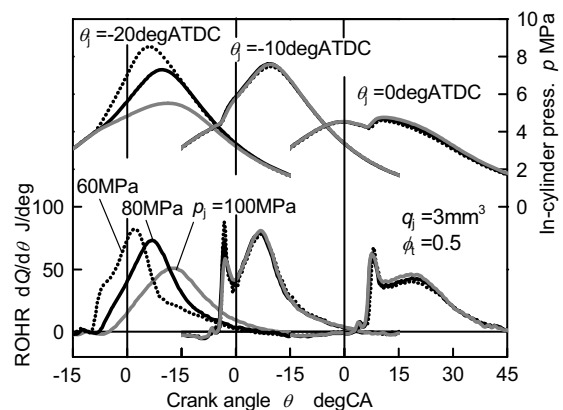


Fig. 6. Effect of injection pressure on heat release rate and in-cylinder pressure.