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Research Paper

High load expansion with low emissions and the pressure rise rate by dual-fuel combustion

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HIGHLIGHTS

- Dual-fuel PCI combustion strategy implemented in a light duty diesel engine.
- The engine could be operated in dual-fuel PCI mode over WLTP cycle (1500 rpm).
- Acceptable intake pressure for the high load condition was possible.
- Propane/diesel dual-fuel combustion could reduce mPRR while maintaining high gITE.
- Over 80% of NOx and 65% of Soot could be reduced compared to CDC.

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ABSTRACT

The combustion process using two different fuels with different reactivity is known as dual-fuel combustion. Many studies have proven that dual-fuel combustion has a positive prospect in future combustion to achieve near-zero NOx (nitrogen oxide) and soot emissions with high indicated thermal efficiency. However, it has a limitation while expanding high-load conditions because of the high mPRR (maximum in-cylinder pressure rise rate) under light-duty diesel engine. Thus, it is important to establish the operating strategy with dual-fuel combustion to achieve a low mPRR while maintaining high-efficiency and low-emission combustion in high load conditions.

This study describes a detailed process of emission and the mPRR reduction under 1500 rpm/gIMEP (gross indicated mean effective pressure) at 14.5 bar. Operating parameters such as the fuel rate, diesel injection timing and EGR (exhaust gas recirculation) were changed to find the suitable point for the low emissions and mPRR. Stable combustion was possible with only a small amount of diesel injection (5% to total LHV (low heating value) of fuels) because the high compression ratio helped the ignition process. After the ignition occurred with the diesel fuel, the combustion process with stabilized propagation and auto-ignition began for the low-reactivity fuel. This process helped to reduce the mPRR and provided faster combustion, which is positive for the increase in gITE (gross indicated thermal efficiency). The result indicates that the mPRR can be less than 7 bar/deg, whereas the load condition is as high as gIMEP 14.5 bar. Lower NOx and soot emissions and higher gITE were also achieved compared to the neat diesel combustion case.

1. Introduction

In the past, the diesel engine was considered as clean and powerful combustion system. However, since global warming and emission issues have been the largest concern worldwide, CO2 (carbon dioxide) regulation and emission regulations are strengthened. In addition, the test driving cycle has become more stringent and changed from NEDC (new European driving cycle) to WLTP (world harmonized light vehicle test procedure) and RDE (real driving emissions). Although adequate uses of after-treatment systems such as DPF (diesel particulate filter), LNT (lean NOx trap) or SCR (selective catalytic reduction) have been applied, this equipment requires high manufacturing costs and causes a pressure increase in the exhaust manifold, which provokes pumping loss. Thus, it is important to reduce the engine-out emissions by improving the engine combustion process.

Many diesel engine researchers are attempting to develop new

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combustion technologies for the high efficiency and low emissions to overcome the problems that the diesel engine is facing [1,2]. Premixed combustion with early diesel injection timing, which is called PCCI (premixed charge compression ignition), is a promising combustion strategy to simultaneously reduce NOx (nitrogen oxides) and soot emissions [3,4]. Normally, the concept of PCCI combustion implies that the SOC (start of combustion) is later than the EOI (end of injection) to secure a long ignition delay to improve the air-fuel premixing ratio. Thus, the PCCI combustion has low soot and NOx emissions but has a limitation on expanding load conditions such as HCCI (homogenous charge compression ignition) combustion because of the high mPRR (maximum in-cylinder pressure rise rate) [5].

Based on the PCCI combustion concept, RCCI (reactivity controlled compression ignition) was introduced to improve the air-fuel mixing ratio compared to the diesel PCCI system. RCCI, which is also called as dual-fuel PCCI, has become a promising technique because of its high thermal efficiency and notably low NOx and soot emissions [6,7]. In the RCCI concept, a low-reactivity fuel (e.g., gasoline or propane) is introduced as a premixing source and directly injects the high-reactivity fuel (e.g., diesel or jet fuel) for the ignition source [8,9]. Unlike the CDC (conventional diesel combustion), the RCCI combustion focuses on the fuel reactivity in the cylinder, which can be considered as stratified reactivity condition. Thus, the SOC timing is not controlled by the diesel injection timing but by the degree of reactivity stratification and overall equivalence ratio. Therefore, it is difficult to define the combustion phase by changing the injection timing [10].

However, dual-fuel PCCI combustion shows several limitations on expanding load conditions. Although it has superior characteristics with low emissions, unstable combustion with high CO emissions occur under low load condition, and the high mPRR and knock phenomena are the main problems at high-load conditions under light duty engines. Thus, expanding low load limit with optimized RCCI was studied. Murugesa et al. [11] have experimentally optimized the low load RCCI on light duty diesel engine. They have changed the compression ratio and found that the lower compression ratio shows higher thermal efficiency with lower level of emissions. However, CO and HC emissions were much higher than high compression ratio case and CDC.

Expanding the upper load range by using various strategies has been studied by many researchers. Curran et al. explored the high efficiency and low NOx and soot emissions of RCCI with gasoline and diesel fuel in a wide range of speed and load conditions in a light-duty diesel engine [12]. However, the result shows that the load and speed limit of the RCCI combustion were half of the CDC load limit. The mPRR, which caused a vibration and noise problem, was over 10 bar/deg, and the THC and CO emissions were too high under low load condition. Yang et al. [13] have changed the fuel blending ratio (gasoline and diesel), and have tested for the low emissions and high efficiency combustion schemes under wide operating range. However, under high load combustion, CDC showed the better efficiency while having the same level of NOx and Soot emissions. Tong et al. [14] have used PODE (polyoxymethylene dimethyl ethers) as a high reactivity fuel, and compared with diesel dual-fuel combustion under HD engine. They concluded that the low energy injection ratio of PODE prolong the combustion duration with latter injection, and the combustion was stable due to the high cetane number of PODE and showed low emissions level, but the pressure rise rate was little higher. Other studies to expand the load limits by changing the combustion chamber (piston shape) were conducted. Hanson et al. showed better load performance with modified RCCI piston shape than the conventional piston shape considering the gITE (gross indicated thermal efficiency) and combustion efficiency, but the NOx emissions were much higher than those of the CDC condition [15]. Dempsey et al. have also shown that RCCI piston shape improves 2–4% of thermal efficiency than the stock piston and using methanol-diesel dual-fuel combustion expands higher load conditions [16]. Benajes et al. [17] baptized the three different combustion mode which is differed by its operating load conditions. Under high load condition, dual-fuel diffusion scheme was used in this paper, which the diesel injection timing is similar to that of conventional diesel combustion. Since the combustion mode is not premixed combustion, soot emission is high as CDC.

Using gaseous fuel such as CNG (compressed natural gas) as a low-reactivity fuel was also widely studied for dual-fuel combustion experiments, particularly for heavy-duty engines [18,19]. Since introducing the gasoline fuel through the intake port can cause wall wetting, which decreases the volumetric efficiency and increases THC emissions because the diesel intake port normally has a swirl motion. Thus, the gasoline fuel cannot reach the intake valve and evaporate well [20].

Based on the literature survey, it is observed that RCCI is promising LTC strategy to achieve low emissions with high thermal efficiency. Under light duty engine however, it was hard to achieve low emissions level with low pressure rise rate (under 10 bar/deg) in high load expansion cases. Therefore, the main objective of this study is to provide the potential of high load expansion over WLTP region without knock or high mPRR and higher gITE. Using gaseous fuel such as propane which has a higher octane number than gasoline can be used in relatively high compression ratio engines because the knock resistance increases. Also, it is to observe much lower emissions level than CDC condition with the propane/diesel dual-fuel combustion in high compression ratio light duty diesel engine. To achieve such a performance, changing the low-reactivity fuel rate and diesel injection timing was considered. Since the engine has high compression ratio, the micropilot injection strategy was dealt which is enough for the combustion to occur. It is to achieve low pressure rise rate and soot emission. Also, early injection strategy to improve premixing condition with high EGR rate was considered to achieve low emissions. The target engine operating condition was set at 1500 rpm/gIMEP 14.5 bar (gross indicated mean effective pressure), which is over the WLTP range at this rpm. To compare the NOx and soot emissions and gITE, CDC was conducted with neat diesel combustion in an identical engine. The mPRR value was limited to 10 bar/deg as a combustion characteristic parameter. The constraints for NOx and soot emissions were applied to reduce more than 50% each compared to CDC while maintaining gITE. The CoV (Coefficient of Variation) of gIMEP was limited to less than 5% for all cases to ensure stable combustion [21].

2. Experimental setup

2.1. Experimental setup

Fig. 1 shows the schematic diagram of the experimental setup. The experiment was conducted on a single-cylinder diesel engine with a 395 cc displacement. Only a few minor changes to the propane injection system were made to the baseline engine. The propane fuel was fumigated by the gaseous state with 2 bar through the intake port. The diesel fuel was directly injected by 850 bar with a Bosch piezo injector, which could inject up to 1800 bar. The injection pressure was relatively low since the cylinder pressure of the injected diesel is lower than that in the CDC condition. The fuel ratio was calculated based on the LHV of each fuel. The diesel fuel temperature was controlled at 36 °C, and the propane temperature was 25 °C during the experiment. The intake pressure was fixed at 1.6 bar, which is normally the maximum value at 1500 rpm for a CDC engine. The engine specification is based on the EURO V standard, which has a compression ratio of 17.3. The engine was equipped with a DOHC (double over-head cam) and a diesel conventional piston. A supercharger system was used in return for the turbocharger and EGR input system. The EGR and air were simultaneously compressed using a supercharger, and the EGR ratio was controlled by an EGR valve. The intake temperature was controlled at 27–30 °C during the experiment. The EGR system was similar to that of the LP (low pressure) EGR system since the EGR was introduced after passing through the DPF system and EGR cooler. A 15 L steel chamber was set after the EGR cooler to maintain the EGR rate and avoid