Full Length Article

Improvement of combustion and emissions with exhaust gas recirculation in a natural gas-diesel dual-fuel premixed charge compression ignition engine at low load operations

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ABSTRACT

Dual-fuel premixed charge compression ignition (DF-PCCI) combustion has been demonstrated as a promising solution for simultaneous reduction of nitrogen oxides (NO_X) and particulate matter (PM) emissions in heavy-duty compression ignition engines. The use of natural gas (NG) as the low-reactivity fuel in DF-PCCI combustion can expand the limited range of high load operations owing to the lower reactivity of NG than that of gasoline. However, the lower reactivity of NG results in significant hydrocarbon (HC) and carbon monoxide (CO) emissions at the low load operations. In this study, the mixture formations with and without exhaust gas recirculation (EGR) in NG-diesel DF-PCCI combustion were assessed to reduce the HC and CO emissions as well as to improve the fuel economy at low load operations. Diesel injection timing and NG substitution ratio (SR), which is defined as the proportion of energy stored in NG with respect to the total energy amount, were changed to examine the effects of the mixture formation on the DF-PCCI combustion. The NG SR, which was required to maintain the combustion phasing at a constant crank angle degree (CAD), was increased as the diesel injection timing was retarded in the mixture formation without EGR. The introduction of EGR, in addition to the diesel injection timing and the NG SR, contributed to the favorable mixture formation for the low load operations. The NO_X and PM emissions were lower than the EURO VI limitations in both the mixture formations with and without EGR. When the EGR rate of 50% was applied, the indicated thermal efficiency (ITE) increased compared to the case without EGR. The increased ITE was due to the improved combustion efficiency, the higher peak heat release rate (HRR), and the shorter combustion duration. The HC and CO emissions also decreased significantly with the EGR.

1. Introduction

Diesel engines have been implemented in numerous applications owing to their high fuel conversion efficiency and high maximum brake mean effective pressure (BMEP) levels. However, diesel engines should now comply with carbon dioxide (CO_2) and other exhaust gas emissions regulations [1]. In particular, nitrogen oxides (NO_X) and particulate matter (PM) emissions from the diesel engines represent a significant challenge because NO_X and PM emissions are produced in the high combustion temperature regions of a stoichiometric fuel–air mixture on the periphery of the diesel spray and the high temperature of the fuel-rich regions in the core of the diesel spray, respectively [2]. Conventional diesel combustion (CDC) requires after-treatment devices, such as selective catalytic reduction (SCR) and diesel particulate filter (DPF),

to comply with EURO VI regulations for heavy-duty diesel engines. However, implementing such after-treatment devices increases the vehicle cost and causes the fuel economy to deteriorate [3]. Therefore, a combination of engine-out emissions reductions and advanced after-treatment systems is required to fulfill the more stringent emissions regulations.

Various types of single-fueled in-cylinder combustion technologies, including homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), low temperature combustion (LTC), and gasoline compression ignition (GCI), have been developed over the past few decades to obtain low engine-out NO_X and PM emissions. These combustion technologies utilize a long ignition delay, which reduces the local equivalence ratio of the premixed fuel–air mixture. The low combustion temperature of the premixed fuel–air mixture can avoid regions with high NO_X and PM formation during the combustion process [3]. The combustion technologies also have an opportunity to achieve high thermal efficiency owing to the reduction in the combustion duration and the lower heat transfer loss compared to those of CDC [4]. Diesel and gasoline have been utilized as fuel for the combustion technologies because of existing infrastructures. Diesel has a high cetane number and low volatility. Therefore, diesel has an advantage in that it offers stable combustion at low load conditions of the combustion technologies [5]. However, it is hard to control the combustion phasing in the diesel-fueled in-cylinder combustion technologies, which can deteriorate the fuel economy, particularly at the high load conditions. This is because the start of combustion (SOC) is dominated by the chemical kinetics of the premixed fuel–air mixture [3]. The level of pressure rise rate (PRR) is also too high to operate the engines with diesel in-cylinder combustion technologies at the high load conditions, which can induce significant combustion noise and even engine damage [6]. GCI combustion has been proposed to solve the limitations of the combustion technologies with diesel at high load operations. Gasoline has a high octane number and a high volatility, which can improve the fuel–air mixing process. Therefore, the improved control of the combustion phasing can be achieved with gasoline at the high load operations because of the higher resistance against the auto-ignition of gasoline than that of diesel [7–9]. However, its higher resistance against the auto-ignition induces combustion instability and high levels of hydrocarbon (HC) and carbon monoxide (CO) emissions at the low load operation of the GCI combustion [10,11]. The level of PRR is also high due to the volumetric heat release of the premixed gasoline-air mixture.

Dual-fuel premixed charge compression ignition (DF-PCCI) combustion is based on the idea that different fuel properties are required for in-cylinder combustion technologies under different engine operating conditions [12]. In particular, a high cetane number fuel is required at the low load operations, while a high octane number fuel is required for the high load operations. DF-PCCI combustion, including reactivity controlled compression ignition (RCCI) and dual-fuel combustion, employs in-cylinder fuel blending with two fuels of different reactivity [13]. The blending ratio of the two fuels can be employed to control the combustion phasing, in addition to the injection timing of the direct-injected fuel and exhaust gas recirculation (EGR), which are used to control the combustion phasing of the single-fueled in-cylinder combustion technologies. The excessive PRR of the single-fueled in-cylinder combustion technologies can be also reduced in the DF-PCCI combustion because the staged consumption of the high-reactivity fuel followed by the low-reactivity fuel extends the heat release [14]. Much research has demonstrated that gasoline-diesel DF-PCCI combustion can be operated with NO_X and PM emissions under the EURO VI

limitations from low to high load conditions [15–18]. The diesel portion should increase to prevent incomplete combustion at the low load operations, while the gasoline portion and the EGR rate should increase to control the combustion phasing and suppress the PRR at the high load operations. Although the operating range is expanded compared to that of the diesel-fueled in-cylinder combustion technologies, the high load operation is still limited due to the excessive PRR [19,20].

Natural gas (NG) is a promising fuel in transportation sector because of its low carbon-to-hydrogen ratio and price competitiveness [21,22]. As the low-reactivity fuel for DF-PCCI combustion, NG has the advantage of expanding the high load limit, because of the lower reactivity of NG than that of gasoline [23–25]. Walker et al. [23] compared methane-diesel DF-PCCI combustion and gasoline-diesel DF-PCCI combustion in a heavy-duty single-cylinder engine under high load conditions. The use of methane in the DF-PCCI combustion allowed for significant high load extension, mainly because of the increased combustion duration and thus the reduced maximum PRR, over the gasoline-diesel DF-PCCI combustion. The load was expanded up to 17.3 bar gross indicated mean effective pressure (IMEP) in the methane-diesel DF-PCCI combustion. The experimental and computational analysis by Dahodwala et al. [24] shown that NG-diesel DF-PCCI combustion was operated up to 14 bar BMEP by introducing EGR and double injection at 1800 revolutions per minute (rpm). However, the high load operation was limited at 1500 rpm because of excessive peak pressure and maximum PRR. Injection mass split and a reduction in injection pressure allowed the DF-PCCI combustion to operate at 1500 rpm. Nieman et al. [25] investigated NG-diesel DF-PCCI combustion at a wide range of engine speed and load by the multi-dimensional computational fluid dynamics (CFD) code KIVA-3 V in conjunction with the CHEMKIN chemistry tool. The engine was operated up to 23 bar IMEP in the DF-PCCI combustion with a high EGR rate, a high NG portion, and double injection strategy, with an optimization of the injection timing and the injection mass split. Although the NG-diesel DF-PCCI combustion has many advantages as listed above, it is difficult to commercialize it because of the following disadvantages [25–30]. The DF-PCCI combustion suffers from high HC and CO emissions at low load operations because the reactivity of NG is lower than that of gasoline. The computational analysis by Nieman et al. [25] shown that very low NO_X and PM emissions were obtained from low to mid load conditions without the use of EGR. However, a low gross efficiency and high levels of HC and CO emissions were observed at 4 bar IMEP because the low reactivity of NG reduced the combustion efficiency. The experimental demonstration of NG-diesel DF-PCCI combustion by Doosje et al. [26] was conducted in an inline six-cylinder diesel engine. The DF-PCCI combustion was operated from 2.5 bar to 9 bar BMEP with low NO_X and PM emissions at 1800 rpm without EGR. A considerable fuel consumption was found at 2.5 bar BMEP mainly because of the relatively larger friction losses and the longer combustion duration. The HC and CO emissions also increased significantly at the low load condition. Gharehghani et al. [27] compared NG-diesel DF-PCCI combustion and conventional diesel combustion in a single-cylinder engine. The combustion loss of the DF-PCCI mode was higher than that of the conventional diesel mode, while the heat loss was reduced significantly in the DF-PCCI mode compared to that in the conventional diesel mode. The HC and CO emissions increased significantly in the DF-PCCI combustion at the low load conditions. The use of biodiesel as the high-reactivity fuel in the DF-PCCI combustion was effective in reducing the HC and CO emissions compared to diesel. Hutter et al. [28] investigated the reasons for the low load limitations of a NG-diesel dual-fuel engine using a physical engine model. Unburned HC emissions increased significantly at the low load operation because of the lower fuel–air equivalence ratio. The HC emissions were reduced using throttling, which increased the equivalence ratio, at the expense of the engine efficiency. The engine efficiency improved by introducing EGR without increasing the HC emissions. Yousefi et al. [29] and Wang et al. [30] pointed out that the premixed NG-air mixture is very lean at low load operations of DF-PCCI