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Full Length Article

Performance and emissions of gasoline Homogeneous Charge Induced Ignition (HCII) by diesel through whole operating range on a heavy-duty multi-cylinder engine

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HIGHLIGHTS

- Homogeneous Charge Induced Ignition (HCII) is tested on a multi-cylinder engine from 25% to 100% engine load.
- CFD coupled with chemical kinetics are conducted with grid *Adaptive Mesh Refinement* and *Fixed Embedding*.
- A gasoline ratio of 70–80% is recommended to avoid both incomplete combustion and high pressure rise rate.
- HCII combustion turns out to be an effective strategy to reduce NOx and soot emissions at the same time.
- HCII strategy shows a great potential of meeting Euro V limitations only with the Diesel Oxidation Catalyst (DOC).

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ABSTRACT

Recently the performance of dual fuel strategy on multi-cylinder engines over the whole engine map has received increasing attention. This research focuses on the potential of Homogeneous Charge Induced Ignition (HCII) combustion fueled with gasoline and diesel meeting Euro V emission standard through the whole operating range using a simple after-treatment system. This combustion mode utilizes a port injection of high-volatile fuel (gasoline) to form a homogeneous charge and a direct injection of high ignitable fuel (diesel) near the Top Dead Center (TDC) to trigger combustion. In this paper, an experimental and numerical investigation of the combustion characteristics and emission formation of HCII on a multi-cylinder heavy-duty engine is conducted. The effects of gasoline ratio (R_g), one of the most important parameters in dual-fuel mode, are explored and analyzed in detail. A R_g of 70–80% is recommended for better combustion and emission performance at the operating condition in this paper. HCII also turns out to be an effective strategy to reduce NOx and soot emissions at the same time. Furthermore, the high THC and CO emissions of HCII combustion can be eliminated using Diesel Oxidation Catalyst (DOC). Then the HCII strategy was optimized through the whole operating range showing a great potential of meeting Euro V limitations only with DOC as an after-treatment device. The fuel consumption also reduced with dual fuel strategy.

1. Introduction

Internal combustion engines (ICE) still remain one of the most significant sources of driving power in modern society. Driven by the global concern over energy saving and environmental protection, advanced combustion technologies have been the focus of ICE development in recent years. It is well known that conventional ICEs can be classified into Compression Ignition (CI) engines and Spark Ignition (SI) engines according to different fuels, fuel-air mixing processes and the combustion modes. However, it is always a big challenge for CI engines to defeat the trade-off between NOx and soot emissions caused by diffusion combustion. As for SI engines, due to low compression ratio, high pumping loss, large cycle variation and difficulty to achieve lean-burn, the thermal efficiency can hardly catch up with that of CI engines. To solve these conventional problems in ICEs, some novel combustion modes have been proposed, such as Homogeneous Charge Compression Ignition (HCCI) and Premixed Charge Compression Ignition (PCCI), etc. Both

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low emissions and good fuel economy can be realized in these combustion modes. However, in these modes it is very hard to control the auto-ignition timing and the operating range is limited [1].

Another possible strategy to achieve high efficiency and low emissions is dual-fuel combustion [2] which merges the advantages of both CI and SI engines. Dual-fuel combustion has been studied by many research institutions and received increasing interest in recent years. Reactivity Controlled Compression Ignition (RCCI) proposed by Kokjohn and Reitz et al. [3] is a promising dual-fuel combustion strategy that uses premixed mixture of low reactivity fuel and early-cycle direct injections of high reactivity fuel. With multiple injections, the in-cylinder fuel reactivity can be controlled in RCCI to optimize the combustion process [4]. Kokjohn et al. made comparisons between Conventional Diesel Combustion (CDC) and RCCI [5]. The results showed that the NOx and soot emissions were significantly reduced in RCCI and higher efficiency was achieved. Splitter et al. found that the gross thermal efficiency for RCCI could be near 60% [6]. RCCI combustion exhibits the potentials of dual-fuel combustion to realize clean and highly efficient combustion and is widely studied even with other fuel combinations [7–13]. However, RCCI is also challenged by some problems such as how to extend the operating range. Benajes et al. studied the potential of RCCI combustion meeting stringent emission regulations in a heavy-duty single-cylinder engine over the whole engine map [14]. It was found that the RCCI operating range was limited by high Peak Pressure Rise Rate (PPRR). With a compression ratio of 14.4:1, RCCI engine mapping was only possible to reach 50% engine load. Full engine load was fulfilled with a lower compression ratio of 11:1.

There is another possible dual fuel combustion mode named Homogeneous Charge Induced Ignition (HCII) [15,16]. This mode utilizes a port injection of high-volatile fuel (gasoline) to form a homogeneous charge and a direct injection of high ignitable fuel (diesel) near the Top Dead Center (TDC) to trigger combustion. Since HCII aims at providing an effective control of HCCI combustion with diesel direct injections near TDC, a certain amount of diffusion combustion may exist. Thus, the operating range of HCII could be extended to full load. On the contrary in RCCI both low and high reactivity fuels are injected at early crank angles and the in-cylinder fuel reactivity is optimized [4]. It was found that the high thermal efficiency comparable to diesel engines could be achieved in HCII [15,16]. Chang et al. found that with a relatively low injection pressure, HCII could achieve low soot emissions which was comparable to that of CDC with high injection pressures [17]. Ren et al. conducted a numerical study of HCII and it was confirmed that the diesel injection could act like an effective ignition source, providing a direct control of the combustion phasing [18]. Yu et al. studied the three different heat release modes in HCII and found that the rapid two-stage combustion mode in HCII featured higher thermal efficiency, reduced NOx and soot emissions and smoother pressure rise rate [19]. Gao et al. compared the single and double injection strategies in HCII over diesel injection timing sweep and Exhaust Gas Recirculation (EGR) sweep [20]. It was found that compared to single injection strategy, the HC, CO and NOx emissions of double injection HCII were significantly lower and the combustion efficiency was improved while remaining a low level of soot emissions.

With the advances in computational hardware, Computational Fluid Dynamics (CFD) coupled with chemical kinetics has been playing a significant role in the development of ICE research. To some extent, the engine experimentation is limited by high cost and excessive time while modeling study has shown its advantages in these aspects. Besides, the in-cylinder combustion characteristics and emission formation obtained by numerical simulation could be visualized to provide a better understanding of the engine working process [21]. Li et al. investigated the effects of several important engine parameters on RCCI combustion using numerical modelling: piston bowl geometry [22], fuel ratio and injection timing [23] and reactivity gradient [24]. Yang et al. conducted an experimental and numerical study on different dual-fuel combustion modes with gasoline and diesel [25]. It was found that in the early-diesel-injection dual fuel combustion most of the mixture is uniform in both mixture concentration and reactivity, while there are mixture stratification in late-diesel-injection dual fuel combustion. Besides, Liu et al. studied the combustion and emissions of the *n*-butanol/biodiesel dual-fuel mode by both experimental methods and numerical simulation [26]. It was found a same CA50 can be achieved by both early or late injection in *n*-butanol/biodiesel dual-fuel mode.

Recently the performance of dual fuel strategy on multi-cylinder engines over the whole operating map has received increasing attention. Hanson et al. applied natural gas/diesel RCCI over the full operating map on a Heavy-Duty (HD) engine [27,28]. But it was found that the adaptive injection strategies, which adopt a mixed mode or even a two stage combustion strategy, have to be utilized to realize full load operation with RCCI. However, the NOx and soot emissions still remained at a high level, so traditional after-treatment devices such as Selective Catalytic Reduction (SCR) and Diesel Particulate Filter (DPF) are still needed. On the contrary, this research focuses on the potential of HCII combustion meeting Euro V emission standard using a simple after-treatment system. In this paper, the combustion and emission performance of HCII combustion on a HD multi-cylinder engine was studied with experimental and numerical methods. First, the effects of gasoline ratios, one of the most important parameters in dual-fuel mode, on performance and emissions were explored and analyzed in detail. Then, the HCII strategy was optimized from 25% to 100% original engine load aiming at meeting the Euro V emission regulation only with Diesel Oxidation Catalyst (DOC). The performance and emissions at different engine loads are discussed.

2. Experimental setup

2.1. Engine

All the experiments in this study were conducted on a six-cylinder heavy-duty CI engine which was modified to run in dual-fuel mode. The basic engine specifications are shown in Table 1, along with a schematic of the test engine configuration in Fig. 1. A single stage variable geometry turbine (VGT) turbocharger was implemented providing an absolute intake air pressure up to 0.35 MPa. The EGR valve and cooler could be electronically controlled keeping EGR rate a constant value. The intake temperature was also adjustable utilizing an electronically controlled intake cooler.

Table 1
Engine specifications.

Cylinders	6
Cylinder bore (mm)	108
Stroke (mm)	136
Connecting rod length (mm)	209.7
Displacement (L)	7.47
Compression ratio	18:1
Swirl ratio	1.33
Number of valves	4
Intake valve open (IVO) (°CA ATDC)	−377
Intake valve close (IVC) (°CA ATDC)	−154
Exhaust valve open (EVO) (°CA ATDC)	125
Exhaust valve close (EVC) (°CA ATDC)	−346