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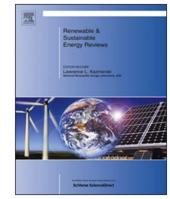

Review on the management of RCCI engines

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ABSTRACT

RCCI (reactivity controlled compression ignition) engines are found to be capable of achieving higher thermal efficiency and ultra-low NOx and PM emissions. The reactivity controlled combustion is accomplished by creating reactivity stratification in the cylinder with the use of two fuels characterized by distinctly different cetane numbers. The low reactivity (i.e., low cetane number) fuel is firstly premixed with air and then charged into the cylinder through the intake manifold; later, the high reactivity (i.e., high cetane number) fuel is injected into the charged mixture through a direct injector. Subsequently, the reactivity stratification is formed. By strategically adjusting the ratio of two fuels and injection timings, the produced reactivity gradient is able to control the combustion phasing and mitigate the pressure rise rate, as well as the heat release rate. Alternatively, structural factors such as CR (compression ratio) and piston bowl geometries can also affect the combustion characteristics of RCCI. Besides the engine management, the fuels that could be utilized in RCCI engines are also crucial to determine the evaporation, mixing, and combustion processes. To gain a comprehensive knowledge on the state-of-the-art of RCCI combustion, detailed review on the management of RCCI engines has been presented in this paper. This review covers the up-to-date research progress of RCCI including the use of alternative fuels and cetane number improvers, and the effects of fuel ratio, different injection strategies, EGR rate, CR and bowl geometry on engine performance and emissions formation. Moreover, the controllability issues are addressed in this article.

1. Introduction

The replacement of horses by engines made the world upside down, especially the combustion engines that convert chemical energy of fuel to forward motion. The engines, utilized in domestic cars, railways, marine ships and jet planes, make global transportation much more convenient compared to the old days. Among the various types of engines, CI (compression ignition) engine reigns supreme partly due to its higher fuel efficiency [1]. CI engines around the world consume lots of fuels and subsequently emit considerable amount of pollutions, particularly serious in NOx and PM. Concerning fuel saving and environmental protection, engine research encompasses the improvement in efficiency and the reduction in emissions.

With effort devoted in the past decades, besides DICI (direct injection compression combustion), some advanced combustion modes in CI engines have been developed, for instance, HCCI (homogeneous charge compression ignition), PCCI (premixed charge compression ignition) and RCCI (reactivity controlled compression ignition). Before the emerging of RCCI, HCCI and PCCI had been studied for decades. The results of studies show that HCCI and PCCI could lead to high efficiency and low emissions [2,3]. However, these two combustion modes are difficult to be realized at high load conditions, because the HRR (heat release rate) is controlled by chemical kinetics which could lead to an unacceptable noise and a high pressure rise rate [4]. To mitigate this issue, fuel management in CI engines is groped. Bessonette et al. [5] tested fuels with a broad range of ignition quality (between gasoline and diesel) in a heavy-duty HCCI engine. They concluded that the ignition quality of fuel should be varied to cover a

Abbreviations: ATDC, after top dead center; BMEP, brake mean effective pressure; CA50, crank angle of 50% heat released; CA, crank angle; CDC, conventional diesel combustion; CI, compression ignition; CO, carbon monoxide; CRI, common rail injector; DDFS, direct dual fuel stratification; DI, direct injector; DICI, direct injection compression combustion; DME, dimethyl ether; DTBP, di-tertiary butyl peroxide; EGR, exhaust gas recirculation; FSC, fast single-stage combustion; GDI, gasoline direct injector; HCCI, homogeneous charge compression ignition; HCII, homogeneous charge induced ignition; HTHR, high temperature heat release; HRF, high reactivity fuel; HRR, heat release rate; IMEP, indicated mean effective pressure; IVC, intake valve close; LRF, low reactivity fuel; LTHR, low temperature heat release; MOGA, multi objective genetic algorithm; MON, motor octane number; MPCI, multiple premixed compression ignition; NG, natural gas; NOx, oxides of nitrogen; NTC, negative temperature coefficient; PCCI, premixed charge compression ignition; PFI, port fuel injector; PM, particulate matter; RCCI, reactivity controlled compression ignition; RON, research octane number; PPRR, peak pressure rise rate; SSC, slow single-stage combustion; SOI, start of injection; TDC, top dead center; TSC, two-stage combustion; UHC, unburned hydrocarbon; ULSD, ultra low sulfur diesel; 2-EHN, 2-ethylhexyl nitrate

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wide range of load and meanwhile reduce emissions significantly. Li et al. [6] examined the effect of diesel/gasoline blend ratio under low, medium and high load conditions in a DICI engine. It was found that to achieve high efficiency, pure diesel is suitable under low load and more gasoline is preferred under high load. Based on the conclusions drawn in Refs. [5,6], it is essential to equip a flexible and robust dual-fuel delivering system considering the stability of cycle-to-cycle operation, as well as the transition from low to high loads.

Though the dual-fuel concept in diesel engine can be dated back to the year as early as 1955 [7], the old-day research mainly focused on the use of gaseous fuel as the premixed fuel such as NG (natural gas), methane, biogas etc. [8,9]. Recently, besides the gaseous fuels, liquid fuels, such as gasoline [10] and iso-octane [11], were also examined. Jiang et al. [10] proposed HCII (homogeneous charge induced ignition) combustion mode where port-injected gasoline is used to form a homogeneous charge and diesel is directly injected into the cylinder with a small amount; then the diesel self-ignites to induce the ignition of the gasoline-air charge. This HCII mode could reduce both NOx and PM emissions. Inagaki et al. [11] studied iso-octane and diesel fueled dual-fuel premixed CI engine in the purpose of spare the necessity on EGR (exhaust gas recirculation). The results showed that the load could be extended to 12 bar by adjusting the ratio of two fuels to form the spatial stratifications of ignitability, even without EGR. Meanwhile, the NOx and smoke were reduced.

However, it is challenging to search the optimized combustion phasing by experimental means due to the unexpected engine knock and misfire, let alone the expenditure on materials and man power etc. With the development of computational tools, 3-D computation can aid the research and the development of novel engines. Kokjohn et al. [12] used KIVA3V coupled with MOGA (multi objective genetic algorithm) [13], an advanced algorithm to search Pareto optimal solution, to optimize operating parameters such as fuel ratio, SOI (start of injection) timing etc. The numerical solution by MOGA acted as a guideline for the experiment. Finally, the experimental results showed that by elaborately choosing operating parameters in dual-fuel PCCI operation, NOx and soot can be controlled below the US 2010 heavy-duty limits with a thermal efficiency about 50%. This dual-fuel PCCI mode was later referred to as RCCI. Thus, to minimize NOx and soot emissions and maximize thermal efficiency, the fuel ratios of low to high reactivity fuels and the injection strategies should be well adjusted. Besides the controlling parameters in an RCCI engine, the structural factors of the engine are also crucial to the combustion process of RCCI. Moreover, fuels with different chemical properties (e.g., ignition ability) and physical properties (e.g., viscosity, volatility etc.) can affect the reactivity stratification in the cylinder.

Thus, to gain a comprehensive view on the state-of-the-art RCCI combustion, this review emphasizes on both fuel management (conventional and alternative fuels) and engine management (controlling and design parameters) in various types of RCCI engines. In the section of fuel management, two fuels strategy and single fuel strategy with additives are summarized with the consideration of fuel properties. In the engine management section, the effects of fuel ratio, factors related to different injection strategies, EGR rate, compression ratio and bowl geometry on the engine performance and emissions formation of RCCI engines are presented. Finally, conclusion and some recommendation on future research direction are given in this paper.

2. Fundamentals of RCCI combustion

2.1. Concept of RCCI

By definition, RCCI is a dual fuel engine combustion technology that uses at least two fuels of different reactivity to realize in-cylinder fuel blending, and adopts multiple injection strategy and appropriate EGR rate to control the in-cylinder reactivity to optimize the combustion phasing, duration and magnitude, thus leading to high thermal efficiency and low NOx and soot emissions [14]. Fig. 1 is a schematic for RCCI combustion. There is a PFI (port fuel injector) in the intake manifold. The LRF (low reactivity fuel), gasoline, is injected through PFI and premixed with air in the cylinder during the intake stroke. The HRF (high reactivity fuel), diesel, is injected through the DI (direct injector) into the cylinder with a single, double or triple injection strategy during compression stroke. The early injected HRF targets the squish region whereas the relatively late injected HRF plays an ignition source role. Then RCCI combustion happens [15].

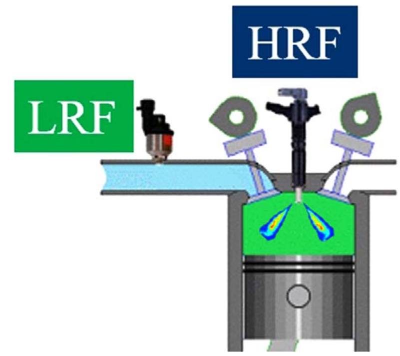

Fig. 1. Schematic on RCCI engine [15].

RCCI combustion is capable of operating over a wide range of engine loads (4.6–14.6 bar) with near zero levels of NOx and soot (meet regulation targets), acceptable pressure rise rate and ringing intensity, and very high indicated efficiency [16,17]. Kokjohn et al. [16] compared RCCI to CDC (conventional diesel combustion) in a single-cylinder engine, it was found that RCCI can significantly reduce NOx and soot emissions, and increase the gross indicated efficiency by about 16.4%. Furthermore, RCCI was tested by Curran et al. [18] on a four-cylinder light diesel engine, and compared to CDC. The brake thermal efficiency of RCCI can reach 39% for the operating condition with engine speed at 2600 rpm and BMEP (brake mean effective pressure) at 6.9 bar, which was improved by 7% compared to CDC. Meanwhile, the NOx was reduced and UHC and CO were increased. The improvement in efficiency and fuel consumption was due to the reduced heat losses, which was about 10% difference compared to CDC [16,17]. Yang et al. [19] also compared RCCI with blend fuel mode. The results showed that the oxidation effect of OH radical derived from the low temperature reaction of diesel fuel determines the heat release process. Compared to the blend mode, the staged combustion from diesel to gasoline can mitigate PPRR (peak pressure rise rate); meanwhile, lower NOx and soot of RCCI were generated.

2.2. Role of reactivity

The reactivity in RCCI combustion mode can be characterized into two types: global reactivity and reactivity stratification [20]. The global reactivity is purely determined by the amount of each fuel and the reactivity indices of fuels (i.e., cetane number and octane number). The reactivity stratification is more unpredictable and is associated with the spray penetration and the entrainment of direct-injected fuel with mixture.

To investigate the role of reactivity stratification, Li et al. [21] numerically compared RCCI combustion with a hypothetical case with the elimination of fuel reactivity stratification, but maintaining the same equivalence ratio. They found that reactivity stratification can retard the ignition timing, reduce HRR, and ease PPRR. This explains the wide cover of engine operating load of RCCI mode. In RCCI mode, except for the reactivity stratification, equivalence ratio and temperature stratifications are also existing. To isolate the effect of reactivity, equivalence ratio and temperature stratifications, Kokjohn et al. [22] used combined analysis of optical diagnostics and chemical kinetic modelling. It was found that reactivity is dominant among three types