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Effects of diesel injection strategy on natural gas/diesel reactivity controlled compression ignition combustion

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A B S T R A C T

The effects of diesel injection strategies on the combustion and pollutant emission characteristics of a modified heavy-duty reactivity controlled compression ignition engine fueled with natural gas/diesel are studied. Natural gas with low reactivity is assumed to be inducted into the engine through the intake port, while diesel fuel with high reactivity is directly injected into the engine using a double injection strategy. Several parameters were studied including the premixed natural gas amount, the first and second injection timings and the injected diesel mass split between the two injections. The results showed improved engine efficiency with reductions in soot and oxides of nitrogen emissions could be achieved with the injection strategies studied, but hydrocarbons and carbon monoxide emissions were deteriorated. Three factors, namely first start of injection timing, second start of injection timing and the diesel injection fuel fractions, had pronounced effects on reactivity controlled compression ignition engine combustion performance and emissions. To reduce soot and oxides of nitrogen emissions, increasing the natural gas percentage, advancing first and second starts of injection timing beyond a certain point and increasing fuel fraction in first start of injection timing are preferred, but they had an adverse effect on hydrocarbons and carbon monoxide emissions.

1. Introduction

The diesel engine has better fuel economy, reliability, and durability compared to petrol engine. However, soot and NO_x emissions have been a challenge for diesel engines due to the heterogeneous nature of CDC (conventional diesel combustion). In addition, improving fuel efficiency is always a goal due to its direct relation to greenhouse gas emissions and crude oil usage. In recent decades, using alternative fuels and switching to promising combustion technologies, such as LTC (low temperature combustion) engines, can be regarded as reliable strategies to reduce NO_x and soot emissions while maintaining high thermal efficiency in CI (compression ignition) engines. Recently, RCCI (reactivity controlled compression ignition) engine aiming at controlling the combustion phasing and engine knock by forming stratified combustion has been proposed by Kokjohn et al. [1] to solve the difficulties of combustion timing control over wide range of engine loads faced by HCCI (homogeneous charge compression ignition) engines. RCCI relies on the stratification (equivalence ratio and PRF (primary reference fuel)) versus homogenization by direct in-cylinder blending different reactivity fuels, hence controlling the combustion phasing [2]. To generate the reactivity in cylinder, fuel with low CN (cetane number), such as gasoline or natural gas, is injected from the port, whereas a fuel with high CN, such as diesel, is injected into the cylinder through an injector [3]. In fact, the reactivity can be categorized into two types: global reactivity; and reactivity gradient. Global reactivity is only determined by the fuel types and their amounts introduced into the cylinder. The reactivity gradient is varied with the injection strategy, because either early or late injection of low and high CN fuels could affect the mixing outcome among the two types of fuel and air [4]. Hence, both the percentage and the injection strategy of each type of fuel could have an impact on the RCCI combustion strategy [5].

The RCCI strategy results in lower emissions of NO_x and soot, high GIE (gross indicated efficiency) compared to CDC [6] and HCCI strategies [5]. Recently, there have been review articles in the literature on RCCI, which provide a comprehensive and thorough study regarding this newly developed combustion mode [7,8].

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Nomenclature

Greek

γ	ratio of specific heats

Abbreviations

ATDC	after top dead center
CA50	crank angle at which 50 percent mass fraction has combusted
CDC	conventional diesel combustion
CO	carbon monoxide
CI	compression ignition
CFD	computational fluid dynamics
CA	crank angle
CN	cetane number
CNG	compressed natural gas
CR	compression ratio
DI	direct-injection
ERC	engine research center
EPA	environmental protection agency
EGR	exhaust gas recirculation
GIE	gross indicated efficiency
HD	heavy-duty
HCCI	homogenous charge compression ignition
HRR	heat release rate
ICE	internal combustion engine
IMEP	indicated mean effective pressure
IVC	intake valve closing
LTC	low temperature combustion
LHV	lower heating value
NOx	oxides of nitrogen
PFI	port-fuel-injection
PCCI	premixed charge compression ignition
PCI	premixed compression ignition
PM	particulate matter
PPC	partially premixed combustion
PRR	pressure rise rate
PPRR	peak pressure rise rate
PRF	primary reference fuel
RCCI	reactivity controlled compression ignition
RI	ringing intensity
RON	research octane number
RPM	revolutions per minute
SCOTE	single cylinder oil test engine
SI	spark ignited
SOC	start of combustion
SOI	start of injection
TDC	top dead center
UHC	unburned hydrocarbon

In an RCCI engine fueled with diesel, the ignition timing can be controlled by adjusting the ratio of diesel and other fuel and varying the SOI (start of injection timing) [9]. Hanson et al. [10] explored effects of fuel blend, SOI and IVC (intake valve closing) timings on dual fuel PCCI combustion. When using a double injection strategy for the diesel injection, as the timing of SOI1 and SOI2 was retarded TDC (toward top dead center), and the mass fraction of diesel fuel injected in the second injection was increased, mixture stratification was enhanced, which then advanced the combustion phasing and increased the PRR and NO_x emissions. In another research, a comparison between E (early) and L (late) injection strategies of high reactivity fuel (i.e., diesel) (E-Single, E-SOI2 and L-SOI2) was experimentally performed on a gasoline/diesel RCCI engine by Ma et al. [11]. It was shown that in controlling the combustion, the mixture reactivity plays a significant role when the diesel fuel is injected earlier; and the mixture stratification plays a considerable role when the diesel fuel is injected later.

Li et al. [12] numerically investigated the mass fraction of premixed methanol, SOI of diesel and initial in-cylinder temperature at IVC on RCCI engine combustion and emissions. The results showed that advanced SOI with a high combustion temperature is desirable for HC and soot reduction, but not for NO_x and CO emissions. Fuel economy was improved and engine knock was avoided by advancing the SOI. Desantes et al. [13] demonstrated that a highly premixed injection strategy for the high reactivity fuel can yield NO_x and soot emissions under EURO VI limits and RI below the target limit.

Meanwhile, energy concerns are prompting researchers looking for alternative fuels in IC engines. NG (natural gas) is an interesting alternative to conventional liquid fuels (i.e., gasoline and diesel) for use in automotive engines [14]. It is a clean burning fuel as compared to conventional liquid fuels like diesel or gasoline. It has a high octane number, and therefore it is suitable for high compression ratio engines [15]. It has a high self-ignition temperature, so it requires an intense source of ignition energy to enable combustion, (i.e., glow plug, spark plug or pilot liquid fuel) [16].

Due to the higher octane number of natural gas compared to gasoline, it can be considered as a better alternative port fuel for RCCI combustion. There have been a few research works published regarding application of natural gas in RCCI combustion. Nieman et al. [17] used the KIVA-3V CFD code in conjunction with the CHEMKIN chemistry tool and the NSGA II algorithm to perform optimization for natural gas/diesel RCCI combustion from low load to high load, adopting a diesel double injection strategy. They found that the double injection strategy was more favorable for an RCCI engine to realize high efficiency and low emissions, while sweeping from low to high load.

Doosje et al. [18] experimentally studied the impact of gas quality in a diesel-CNG RCCI engine. They showed that the SOC slightly changed with earlier injection. They also reported that early timings were not possible with natural gas fraction of 90% due to misfiring. Zoldak et al. [19] examined trade-offs of pollutant emissions, fuel consumption, peak cylinder pressure and PRR in a RCCI engine fueled with CNG and diesel using KIVA-CHEMKIN. Their results showed that the maximum cylinder pressure and PRR were increased in comparison to the baseline diesel case, although both were determined to be within acceptable durability limits. Then, they computationally studied DI-NG (direct injection of natural gas) in RCCI engine and found out that the DI-NG concept creates enhanced stratification of the NG fuel portion and avoids excessive premixing, which tempers the RoPR, thus enables higher load operation [20]. Dahodwala et al. [21] experimentally investigated Diesel/CNG combustion to achieve RCCI combustion. It was demonstrated that RCCI combustion could be achieved at low loads, which enabled even higher CNG substitution and lower emissions. They further numerically evaluated the impact of various control variables, such as boost pressure, EGR (exhaust gas recirculation), injection strategy and rail pressure, on achieving RCCI combustion at 6 bar BMEP, thereby establishing a general framework for in cylinder mixture properties required in realizing RCCI combustion [22]. Bekdemir et al. [23] applied a multi-zone approach to NG-diesel RCCI combustion in a heavy-duty engine. They derived real-time, map-based RCCI models, which are considered to be an