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Evaluation of the necessity of exhaust gas recirculation employment for a methanol/diesel reactivity controlled compression ignition engine operated at medium loads

Yaopeng Li [a], Ming Jia [a,*], Yachao Chang [a], Weiwei Fan [a], Maozhao Xie [a], Tianyou Wang [b]

[a] School of Energy and Power Engineering, Dalian University of Technology, PR China
[b] State Key Laboratory of Engines, Tianjin University, PR China

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ABSTRACT

Three-dimensional computational fluid dynamics simulation was conducted to investigate the improvement of engine performance by managing exhaust gas recirculation rate and methanol fraction in a methanol/diesel reactivity controlled compression ignition engine. By defining fuel efficiency and ringing intensity as the restricted boundaries, the operating ranges of exhaust gas recirculation rate and methanol fraction under various initial temperatures were determined to simultaneously achieve high fuel economy and avoid engine knock. The results indicated that the fuel efficiency and ringing intensity were dominantly affected by the combustion phasing, and they was nearly insensitive to the variations of exhaust gas recirculation rate and initial temperature at a constant combustion phasing. The necessity of exhaust gas recirculation employment at medium loads was dependent on the level of initial temperature. When initial temperature was less than the critical value (380 K in this study), optimal engine performance could be achieved by only adopting high methanol fraction without introducing exhaust gas recirculation. Once initial temperature was beyond the critical value, exhaust gas recirculation was imperative to avoid excessive ringing intensity. Through simultaneously optimizing methanol fraction and exhaust gas recirculation rate, the combined strategy exhibited more advantages in fuel efficiency, nitrogen oxides, and ringing intensity under a wide range of initial temperature.

1. Introduction

Because of the problems of energy crisis and environmental pollution, it is necessary to further improve internal combustion engines with simultaneously high efficiency and low emissions. Even though conventional diesel engines have the advantages over spark ignition engines in fuel efficiency, they suffer more nitrogen oxides (NO_x) and soot emissions. Aftertreatment system could be employed in diesel engines to reduce the exhaust emissions, but an effective aftertreatment system inevitably sacrifices fuel economy and engine cost [1]. Therefore, it is imperative to promote the in-cylinder combustion process for further improvement of fuel economy and reduction of emissions. Recently, low temperature combustion (LTC) strategy has been intensively investigated due to its superiority of high fuel efficiency and low NO_x and soot emissions. For LTC strategy, the sufficiently premixed fuel/air mixture and lean-fuel combustion lead to very low NO_x and soot emissions, and high fuel efficiency can be achieved due to the decreased heat transfer losses and shortened combustion duration [2].

As the representative combustion modes of LTC, homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI) confront two challenges compared to conventional engines. First, the ignition timing is dominantly controlled by chemical kinetics of fuels, which is very sensitive to the temperature, pressure and compositions of in-cylinder charge. Second, the burning rate is not governed by the rate of injection or flame propagation due to the spontaneous compression ignition, resulting in fast heat release process, which confines the extension of operating range to higher loads. Reactivity controlled compression ignition (RCCI) [3] is another effective realization of LTC by utilizing two fuels with different reactivities in two mixing ways, i.e., low-reactive and high-reactive fuels are separately introduced into the cylinder by port and in-cylinder direct injection. Since two fuel supply systems are required in RCCI engines, the cost and complexity of fuel system increase. In contrast with lack of the effective control of combustion phasing in HCCI and PCCI combustion, the

* Corresponding author at: School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, PR China. Tel./fax: +86 411 84706722.
E-mail address: jiaming@dlut.edu.cn (M. Jia).

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Nomenclature

2-EHN	2-ethylhexyl nitrate
ATDC	after top dead center
CA50	50% burn point
DTBP	di-tert-butyl peroxide
EGR	exhaust gas recirculation
EISFC	equivalent indicated specific fuel consumption
EVO	exhaust valve opening
gRNG	generalized re-normalization group
HCCI	homogeneous charge compression ignition
HRR	heat release rate
IMEP	indicated mean effective pressure
IVC	intake valve closing
KH–RT	Kelvin Helmholtz–Rayleigh Taylor
LTC	low temperature combustion
NO_x	nitrogen oxides
OH	hydroxyl radical
PCCI	premixed charge compression ignition
QSOU	quasi-second-order-upwind
RNG	re-normalization group
TDC	top dead center
$[CO_2]_{in}$	CO_2 concentration in the intake manifold
$[CO_2]_{amb}$	CO_2 concentration in the ambient
$[CO_2]_{ex}$	CO_2 concentration in the exhaust manifold
m_d	mass of diesel
m_m	mass of methanol
H_d	lower heating value of diesel
H_m	lower heating value of methanol
W_i	indicated work
$(dp/dt)_{max}$	maximum in-cylinder pressure rise rate
γ	ratio of specific heat
p_{max}	maximum pressure
T_{max}	maximum temperature
R	ideal gas constant

ignition timing of RCCI combustion can be flexibly controlled by adjusting the ratio of high-to-low reactivity fuel. Moreover, due to the fuel reactivity stratification in the cylinder, when the mixture is compressed to the ignition temperature, the in-cylinder auto-ignition sites subsequently grow along with the reactivity gradient [4]. As a result, the combustion process of RCCI is smoother than that of HCCI and PCCI, which is beneficial for the extension to high loads.

Kokjohn et al. [5] investigated the RCCI combustion with gasoline and diesel blends in a heavy duty engine. The results disclosed that high gross efficiency, low ringing intensity (RI), and low NO_x and soot emissions can be achieved simultaneously in a wide load range. Furthermore, aiming at the control of ignition timing of RCCI combustion, Kokjohn et al. [6] investigated the gasoline/diesel RCCI combustion in both light and heavy duty engines. It was found that the combustion phasing changed linearly with the variation of gasoline mass fraction in both size engines. Hence, a predictable ignition timing could be obtained by varying the gasoline percentage. With the help of numerical simulation, Splitter et al. [7] explored the evolutions of several important species in RCCI combustion fueled with gasoline/diesel and E85/diesel blends. It was indicated that the consumption of diesel and the buildup of formaldehyde were later in E85/diesel than those in gasoline/diesel. In addition, the oxidation rate of hydroxyl radical (OH) was more moderate in E85/diesel RCCI combustion. It implied that RCCI combustion was not only related to the ratio of high-to-low reactivity fuel, but also highly dependent on the chemical kinetics of the fuel blends.

Methanol is a widely available and renewable fuel [8], which is capable of serving as an attractive alternative fuel. There is an oxygen atom and no carbon–carbon bonds contained in methanol molecule, both of which are beneficial to the oxidation of fuel. Therefore, methanol has been extensively investigated as a clean fuel. Li et al. [9] investigated the effects of methanol addition on the control of 50% burn point (CA50) in a methanol/diesel RCCI engine under medium loads. It was demonstrated that the optimized ignition timing can be obtained by adjusting methanol fraction. Besides high fuel efficiency, low NO_x and soot emissions, as well as acceptable RI can be achieved simultaneously by adopting high initial temperature and large methanol fraction. By utilizing the diesel/methanol compound compression (DMCC) system proposed by Yao et al. [10], Liu et al. [11] experimentally explored the effects of injection timing and methanol fraction on engine performance in a six-cylinder heavy-duty diesel engine. The results revealed that the trade-off relationship between NO_x and soot emissions was defeated by increasing methanol fraction. However, the increases of HC and CO emissions were also discovered in DMCC combustion.

Due to the thermal, chemical, and dilution effects of exhaust gas recirculation (EGR), introduction of EGR is one of the most effective pathways to reduce NO_x emissions and RI as concluded by Chen et al. [12], so high EGR rate is usually utilized in LTC strategies. Hardy and Reitz [13] conducted a series of diesel PCCI experiments in a heavy-duty engine at 60% load, and it was revealed that both NO_x and soot emissions were compliant to the 2010 emission mandates by employing as high as 75% EGR rate. In addition, the effects of EGR on mitigating the peak of heat release rate (HRR) and RI were extremely obvious as found by Park and Bae [14].

Although the reduction of combustion temperature and retardation of ignition delay are usually required in conventional diesel and PCCI engines by employing EGR, they are not the major obstacles for RCCI combustion due to its adequately premixed fuel/air mixture, lean combustion, and flexible adjustment of fuel reactivity. The effects of EGR on RCCI combustion have been conducted in several related works, and the results demonstrated that the employment of EGR can be avoided by optimizing the injection parameters at low loads [15]. On the contrary, the introduction of EGR is indispensable at high loads to achieve both low NO_x emissions and low RI [16]. Whereas, the importance of introducing EGR into RCCI combustion at medium loads has not been well clarified yet. Moreover, the performance of RCCI engine is highly dependent on the properties of fuel. However, most of previous RCCI investigations focus on gasoline/diesel, and the RCCI combustion fueled with methanol and diesel has not been well understood yet.

In our previous work [9], it was revealed that around 30% EGR rate combining with high initial temperature was favorable to achieve good engine performance at medium loads. However, it must be noted that the influences of EGR on ignition and combustion characteristics of RCCI engines under various initial temperatures have not been comprehensively understood yet. Moreover, the negative effect of EGR on fuel efficiency was not deeply discussed in the previous work [9]. Hence, in this study, the influences of EGR on engine performance are explored under a large range of initial temperature, and the feasibility of RCCI combustion without introducing EGR is revealed to further improve fuel efficiency while maintaining low RI and NO_x emissions simultaneously. Then the relationship between EGR rate and initial temperature is established, and the necessity of EGR employment in diesel/methanol