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Effect of bioethanol on combustion and emissions in advanced CI engines: HCCI, PPC and GCI mode – A review

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HIGHLIGHTS

- The advanced CI engines such as HCCI, PPC, and GCI fueled with bioethanol are discussed.
- The mixture preparation strategies in bioethanol fueled HCCI combustion are classified.
- The different ethanol oxidation models are summarized.
- PRR, RI and noise meter for knock limit and COV_{IMEP} for misfire limit are analyzed.
- HC and CO emissions are still one of challenges for advanced CI engine fueled with bioethanol.

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ABSTRACT

This review mainly concerns the use of bioethanol in advanced compression ignition (CI) engines. Various advanced CI engines are in existence, and this review discusses, homogeneous charge compression ignition (HCCI) combustion, partially premixed combustion (PPC) and gasoline compression ignition (GCI) combustion for discussion. Four different experimental configurations were adopted to measure the autoignition or ignition delay time for ethanol in HCCI combustion mode. The mixture formation strategies in bioethanol HCCI combustion can be categorized into three groups: external, internal and combined mixture preparations. The external mixture preparation is subdivided into port fuel injection and a vaporizer, and the internal mixture preparation into early, late and multiple direct injections. A numerical simulation for ethanol HCCI combustion was recently carried out with a direct numerical simulation and large eddy simulation. The different reduced chemical kinetic mechanisms for ethanol oxidation models present in the literature are summarized in detail. Detailed mechanisms including 57 species and 383 reactions were employed in numerical simulations of ethanol HCCI combustion.

The pressure rise rate, ringing intensity and noise meter calculation for the knock limit and coefficient of variation of indicated mean effective pressure for misfire limit were used. The pressure rise rate has been extensively adopted for the upper limit of the HCCI and PPC combustion, and the acceptable limit for the maximum pressure rise rate is found to be subjective.

Studies related to PPC and GCI modes fueled with ethanol makes use of – fueling configuration that are divided into single and double injections. A double injection strategy was preferred for ethanol PPC with a combination of 50% EGR and relative equivalence ratio of 0.67. The review of the literature on ethanol PPC and ECI provides an overview of the fueling configuration. Further studies on GCI combustion with ethanol, i.e. ethanol-fueled compression ignition (ECI) are required in the future.

In all advanced combustion modes, NOx and soot emissions are low compared to those of conventional diesel engines, and HC and CO emissions are still high in all advanced combustion concepts.

Abbreviations: aTDC, after top dead center; BMEP, brake mean effective pressure; BSFC, brake specific fuel consumption; bTDC, before top dead center; BTE, brake thermal efficiency; CAD, crank angle degree; CA50, crank angle at 50% mass fraction burned; CFD, computational fluid dynamics; CFR, cooperative fuel research; CI, compression ignition; CN, cetane number; CR, compression ratio; DI, direct injection; DCN, derived cetane number; DEE, diethyl ether; DME, dimethyl ether; DNS, direct numerical simulation; ECI, ethanol-fueled compression ignition; EGR, exhaust gas recirculation; FID, flame ionization detector; GCI, gasoline compression ignition; GDI, gasoline direct injection; HCCI, homogeneous charge compression ignition; HRR, heat release rate; HTHR, high temperature heat release; IMEP, indicated mean effective pressure; IQT, ignition quality tester; ITE, indicated thermal efficiency; ITHR, intermediate temperature heat release; LES, large eddy simulation; LHV, lower heating value; LTC, low temperature combustion; LTHR, low temperature heat release; MON, motor octane number; PCCI, premixed charge compression ignition; PCI, premixed compression ignition; PFI, port fuel injection; P_i, injection pressure; P_{int}, intake air pressure; PPC, partially premixed combustion; PRF, primary reference fuel; PRR, pressure rise rate; PPRR, peak pressure rise rate; RCCI, reactivity controlled compression ignition; RCM, rapid compression machine; RON, research octane number; SA, spark assisted; SCCI, stratified charge compression ignition; SI, spark ignition; TDC, top dead center

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Nomenclature

φ	equivalence ratio (the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio)

1. Introduction

In the next few decades, further improvements in internal combustion engines for transportation are likely to address four key challenges including the use of new fuels, adhering to emissions regulations and control, improving combustion, and introducing advanced concepts to save energy [1]. Compression ignition (CI) engines can be used instead of spark ignition (SI) engines to reduce CO_2 emission in an effort to combat global climate change. Therefore, alternative forms of advanced CI engines that can further reduce NOx and PM emissions and improve the efficiency have received an increasing amount of attention since the 1970s. In the past forty years, several hundred papers have been published on advanced compression ignition engines.

Stanglmaier and Roberts summarized the studies published on HCCI combustion as of 1999 [2] and discussed the potential benefits and barriers that need to be overcome to successfully operate an HCCI engine. In contrast very low emissions of NOx and PM as well as a high thermal efficiency at a partial load, HCCI combustion typically results in a higher hydrocarbon (HC) and carbon monoxide (CO) emissions. There are difficulties in preparing mixture, and poor combustion phasing also needs to improve. They also pointed out that the future development of HCCI-specific fuels is required. Furthermore, the texts reviewed in the literature were mainly reported in the Society of Automotive Engineers, USA [3].

Yao et al. conducted an extensive review of numerical simulations of HCCI engines [4]. They initially discussed five different models in a numerical simulation of HCCI combustion and reviewed the evolution of control strategies for diesel-fueled and gasoline-fueled HCCI combustion. They found that the typical generalized diesel-fueled HCCI combustion modes include: early direct injection HCCI, late direct injection HCCI, premixed/direct-injected HCCI combustion and low temperature combustion (LTC).

The mixture preparation before compression in HCCI engines is based on the principle of a spark ignition engine. Therefore, HCCI combustion can be regarded as a combustion advancement for a spark ignition engine including direct injection spark ignition (DISI) or gasoline direct injection (GDI) [5]. The premixed mixture ignites via compression, as in a compression ignition engine. Therefore, HCCI combustion can be treated as an advanced combustion technique for a compression ignition engine [6]. -In his review of advanced compression ignition engines, he classified it into two groups according to the fuel that has been used, i.e. HCCI for fuels other than diesel and LTC for diesel fuel. However, Musculus et al. categorized LTC into two groups according to the degree of premixing [7], i.e., HCCI and partially premixed compression ignition (PPCI). PPCI includes other terms such as premixed-charge compression ignition (PCCI) and PCI. They focused on developing PCCI, which is used in direct injection, with a more moderate mixing time. The distinction between PPCI and HCCI is that the charge distributions for PPCI are more heterogeneous at ignition than HCCI, and these include fuel-lean and fuel-rich mixtures.

Lu et al. conducted a review of fuel design and management to control next-generation combustion modes [8] and selected HCCI, stratified-charge compression ignition (SCCI) and LTC as the most prominent characteristics of the advanced compression ignition combustion mode. In a discussion of alternative fuels for HCCI combustion, only seven papers discussing alcohol were introduced. However, some studies related to alcohol HCCI combustion were included in a review of numerical simulation of biofuel HCCI combustion by Komninos and Rakopoulos [9]. They classified existing simulation models for biofuel HCCI combustion into three groups: single-zone models, multi-zone models and multi-dimensional models. However, the probability density function (PDF) transport model was not included.

A comprehensive review of fundamental phenomena governing HCCI operation was carried out with a particular emphasis on high load conditions, Saxena and Bedoya [10] defined LTC engines as an emerging technology that offers an alternative to spark ignition and diesel engines. They treated HCCI combustion as one type of LTC that includes reactivity controlled compression ignition (RCCI) or dual-fuel HCCI, partial fuel stratification (PFS), PPCI, and spark-assisted HCCI (SA-HCCI), etc. To avoid and expand the operating limits for HCCI, they discussed several technologies including delayed combustion timing, PFS, LTC with double injection, and, in particular SA-HCCI.

Starck et al. [11] recommended promising ways to achieve low NOx and PM simultaneously with advanced combustion processes such as LTC, that include HCCI, PCCI, and PPCI. Five challenges remain for mass production of HCCI engine including achieving combustion phase control, improving operating range, ensuring a homogeneous charge preparation, addressing cold start and high noise levels, and reducing emissions from unburned hydrocarbon (UHC) and CO [4]. Of these, the mixture preparation and combustion phase control were comprehensively reviewed by Bendu and Murugan [12] due to the importance in determining the efficiency and emissions of HCCI engines. The methods to control combustion phase in HCCI engines can be classified into two groups: altering the mixture reactivity and altering the time-temperature history. The first group includes variations in the properties of the fuel by blending two or more fuels via fuel pre-conditioning, exhaust gas recirculation (EGR), and using fuel additives. Blending various biofuels including alcohol, ethers, biodiesel, etc., was introduced a to control combustion phasing [9]. Among various alcohols, ethanol is a typical biofuel demonstrated in the HCCI combustion control strategies. The second group includes intake air temperature modulations, in-cylinder fuel injection timing, water injection etc.

Imtenan et al. [13] conducted a critical review of the emission characteristics of LTC strategies using diesel and biodiesel. In this review, HCCI, PCCI, PCI and RCCI were included in the LTC attaining strategies. The authors found that diesel-fueled LTC strategies simultaneously decrease NOx and PM but increase UHC and CO emissions while reducing the in-cylinder combustion temperature and oxygen concentration. However, they concluded that biodiesel can reduce UHC and CO emissions relative to diesel during the LTC mode due to the short duration of the premixed combustion and higher oxygen concentration. However their level still remains higher than that of a conventional combustion system.

Johansson [14] recently classified major combustion processes for IC engines as spark ignition (SI) with premixed flame, CI with diffusion flame, and HCCI with bulk autoignition of a premixed charge. He recommended advanced CI engines into six modes: spark-assisted compression ignition (SACI), PPC, RCCI, dual fuel combustion (DFC), pre-chamber flame ignition, pilot-assisted compression ignition (PACI) or diesel pilot combustion (DPC). He explained that SACI is a combination of SI and HCCI, Pre-chamber SI and DFC are a combination of SI and CI,