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Research paper

Evaluation of emissions characteristics in dual-fuel RCCI engines operating with diesel-bioethanol and biodiesel-bioethanol fuel combinations

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ABSTRACT

This study presents a comparative evaluation of Diesel–Bioethanol and Biodiesel–Bioethanol dual-fuel Reactivity Controlled Compression Ignition (RCCI) operations using a custom-built, low-cost common-rail injection system with Arduino-based electronic control. The aim is to identify the optimum start-of-injection (SOI) strategy for reducing emissions in biofuel-fueled RCCI engines, contributing to the development of sustainable and affordable low-emission combustion systems. Experiments were performed under 30 % exhaust gas recirculation (EGR) across a range of SOI timings, with emphasis on nitrogen oxides (NOx), carbon monoxide (CO), and unburned hydrocarbons (HC). Results reveal distinct combustion behaviors between the two configurations: Biodiesel–Bioethanol exhibited earlier combustion initiation due to biodiesel's higher cetane number, achieving lower CO and HC but higher NOx emissions, while Diesel–Bioethanol offered reduced NOx with slightly higher CO levels. Optimal combustion efficiency and lowest emissions were obtained at mid-advanced SOI (15–25 °CA BTDC) for both fuel sets. This work provides new experimental evidence on how fuel reactivity and injection phasing interact in biofuel-based RCCI engines and demonstrates the practical feasibility of low-cost control systems for achieving stable, clean combustion. The findings contribute to the ongoing pursuit of renewable, high-efficiency propulsion technologies aligned with sustainable development goals.

1. Introduction

The development of next-generation internal combustion engines (ICEs) is critical in addressing the twin challenges of energy sustainability and environmental protection. As emissions standards continue to tighten worldwide, ICE research has shifted toward combustion strategies that reduce emissions without sacrificing performance [1–3]. Traditional diesel engines, while efficient and durable, emit considerable amounts of nitrogen oxides (NOx) and particulate matter (PM), which are detrimental to air quality and contribute to climate change [4–8]. To mitigate these emissions, researchers are exploring advanced combustion techniques such as Low Temperature Combustion (LTC), which operates under conditions that produce lower NOx and PM emissions. Low Temperature Combustion (LTC) strategies have attracted significant research interest due to their capability to simultaneously reduce nitrogen oxides (NO_x) and particulate matter (PM) emissions while maintaining high thermal efficiency. By lowering in-cylinder peak combustion temperatures and promoting more homogeneous air–fuel mixing, LTC concepts fundamentally alter conventional diesel combustion pathways, thereby suppressing thermal NO_x formation and soot production [4,9]. Among the prominent LTC approaches are Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI), and Reactivity-Controlled Compression Ignition (RCCI).

HCCI combustion relies on a nearly homogeneous air–fuel mixture that auto-ignites due to compression heating. While HCCI can achieve ultra-low NO_x and PM emissions with high efficiency, its practical application is constrained by limited control over combustion phasing, as ignition timing is governed primarily by fuel chemistry and thermodynamic conditions rather than direct actuation [9]. This results in a narrow operating range and sensitivity to intake temperature, engine load, and residual gas fraction, often leading to combustion instability and excessive pressure rise rates under transient conditions.

PCCI represents an intermediate strategy between conventional

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diesel combustion and HCCI, where partial premixing is achieved through advanced injection timing. Although PCCI improves emissions relative to traditional diesel operation, it still suffers from challenges related to combustion control. Rapid heat release, elevated pressure rise rates, and increased combustion noise have been reported, particularly at higher loads, limiting its operational flexibility [10].

In contrast, RCCI offers enhanced control over combustion phasing by employing two fuels with distinctly different reactivity levels. Typically, a low-reactivity fuel is premixed with air through port injection, while a high-reactivity fuel is directly injected to initiate combustion. This reactivity stratification enables precise regulation of ignition timing and heat release, decoupling combustion control from solely chemical kinetics [11]. As a result, RCCI has demonstrated superior capability in achieving ultra-low NO_x and PM emissions while sustaining high thermal efficiency across a broader operating range compared to HCCI and PCCI.

Among LTC methods, Homogeneous Charge Compression Ignition (HCCI) and Reactivity Controlled Compression Ignition (RCCI) are prominent due to their potential to lower combustion temperatures and enhance combustion control [6,7,12–16]. This study focuses on RCCI engines, which utilize a dual-fuel approach, combining fuels with different reactivity levels to optimize combustion dynamics and minimize emissions.

RCCI engines offer distinct advantages in controlling combustion phasing and emissions through the use of fuels with varied reactivity, such as biodiesel, diesel, and bioethanol. This dual-fuel method facilitates precise adjustments in combustion timing and temperature, achieving efficient low-temperature combustion that addresses the limitations of traditional diesel engines. Previous research has shown that RCCI engines can deliver improved thermal efficiency and reduced NOx and PM emissions compared to conventional compression ignition engines [4,8,15,17–21]. In RCCI combustion, the selection of high- and low-reactivity fuels plays a critical role in controlling ignition timing, heat release, and emissions. Biodiesel has been widely studied as a high-reactivity fuel due to its high cetane number and inherent oxygen content, which promote reliable auto-ignition and more complete combustion. When used in LTC and RCCI engines, biodiesel has been shown to reduce particulate matter (PM) emissions and improve combustion stability compared to conventional diesel, while maintaining comparable thermal efficiency [22,23]. The oxygenated nature of biodiesel further suppresses soot formation, making it well suited for RCCI operation.

Previous studies on low-temperature combustion (LTC) engines have widely examined the use of biodiesel as a high-reactivity fuel, emphasising its potential to reduce emissions and improve combustion efficiency while offering a renewable alternative to conventional diesel. Biodiesel's higher cetane number and inherent oxygen content promote shorter ignition delay and more complete combustion, leading to reduced soot and particulate matter (PM) emissions compared to petroleum diesel [19,23]. These characteristics are particularly advantageous in reactivity-controlled compression ignition (RCCI) strategies, where precise control of combustion phasing enables effective utilisation of fuel reactivity differences.

Beyond emission benefits, biodiesel has been shown to enhance combustion quality and thermal efficiency under LTC conditions. The presence of fuel-bound oxygen improves oxidation kinetics and reduces reliance on exhaust after-treatment systems, contributing to improved overall engine efficiency [24]. Moreover, the renewable nature of biodiesel supports greenhouse gas mitigation and energy diversification, aligning with global sustainability and energy security objectives. However, the literature also reports several limitations associated with biodiesel use, including lower volumetric energy density, potential material compatibility issues, and increased fuel system corrosion. These factors may adversely affect fuel consumption and long-term engine durability, particularly at higher engine loads, necessitating engine calibration adjustments or material modifications [25].

Bioethanol has been extensively studied as a low-reactivity fuel in LTC and RCCI engines due to its high-octane number, oxygen content, and clean combustion characteristics. Prior research consistently reports reductions in PM, carbon monoxide (CO), and unburned hydrocarbon (HC) emissions when bioethanol is employed, attributed to enhanced charge premixing and improved oxidation of fuel-rich zones [26]. Under LTC operation, bioethanol also contributes to lower combustion temperatures, which is beneficial for suppressing thermal NOx formation [27].

In addition to emission improvements, bioethanol enables greater flexibility in combustion phasing control and can enhance thermodynamic efficiency when blended or used in dual-fuel strategies [28]. Nevertheless, its lower energy density compared to diesel can result in increased fuel consumption, while its hygroscopic and corrosive nature raises concerns regarding fuel system compatibility and long-term durability. These challenges highlight the need for optimised fuel blending strategies and engine adaptations to fully exploit the benefits of bioethanol in LTC engines [29,30].

In addition to emission benefits, biodiesel supports renewable energy targets and reduces dependence on fossil fuels. However, its lower energy density and potential material compatibility issues, such as fuel system corrosion and increased maintenance requirements, remain challenges that must be addressed, particularly at higher engine loads [25].

Bioethanol is commonly employed as a low-reactivity fuel in RCCI due to its high-octane number, low cetane value, and high latent heat of vaporization. These properties enable effective control of combustion phasing by delaying auto-ignition and reducing in-cylinder peak temperatures, which contributes to significant reductions in NO_x and PM emissions under LTC conditions [26,31]. The oxygen content of bioethanol also enhances mixture homogeneity and promotes cleaner combustion.

Despite these advantages, bioethanol's low volumetric energy density can lead to increased fuel consumption, while material compatibility and corrosion issues may require fuel system modifications [29,30]. Nevertheless, the combined use of biodiesel and bioethanol in RCCI engines offers a complementary fuel strategy, where biodiesel ensures stable ignition and bioethanol enables precise combustion control, resulting in improved emission performance and enhanced sustainability.

In this context, alternative fuels such as biodiesel and bioethanol have garnered particular attention. The increasing concerns over fossil fuel depletion, greenhouse gas emissions, and energy security have driven interest in renewable alternative fuels. Biodiesel and bioethanol are promising options because they are derived from renewable biomass, offer lower net carbon emissions, and can be produced from locally available resources. These renewable fuels offer environmental benefits due to their renewable nature and potential for lower carbon emissions. Biodiesel, which is typically produced from vegetable oils and animal fats, possesses a higher cetane number than diesel, which leads to better ignition properties, though it often results in higher NOx emissions due to its oxygen content [19,23,32]. Bioethanol, derived from biomass sources like corn and sugarcane, offers high oxygen content and low particulate emissions but is limited by its lower energy density and high volatility, which can affect combustion efficiency [27,28,30,31,33–35]. Their compatibility with existing engine technologies enables an effective transition toward cleaner and more sustainable energy systems.

This study seeks to address a critical gap in understanding the emission characteristics of RCCI engines that operate with diesel-bioethanol and biodiesel-bioethanol fuel combinations. Despite biodiesel and bioethanol's potential to reduce certain emissions, challenges remain in achieving efficient combustion due to each fuel's unique chemical and physical properties. By pairing diesel or biodiesel as a high-reactivity fuel with bioethanol as a low-reactivity fuel, RCCI engines may achieve better control over combustion phasing, effectively