Alternative Fuels in Homogeneous Charge Compression Ignition (HCCI) Engines

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Abstract. This review synthesizes recent advances on alternative fuels for Homogeneous Charge Compression Ignition (HCCI) engines, focusing on biomass-derived blends (e.g., biodiesel, ethanol/butanol mixtures) and hydrogen. HCCI combines the high thermal efficiency of compression ignition with the ultra-low NOx and soot potential of premixed, low-temperature combustion. Biofuels, owing to their inherent oxygen content, generally suppress smoke and NOx but can elevate CO/HC under certain volatility and oxidation constraints; blend composition strongly influences auto-ignition phasing and load range. Hydrogen, with fast kinetics and wide flammability limits, extends stable lean operation and reduces carbon at the tailpipe, yet poses challenges in volumetric efficiency, power density, and combustion control. This paper consolidates evidence on mixture preparation, ignition timing management, and emissions trade-offs, and highlights solutions such as multi-fuel blending, intake heating/boost, variable valve strategies, EGR, and spark-assisted compression ignition to widen the feasible operating map. Future work should co-optimize fuel chemistry and closed-loop control for robust, clean, and efficient HCCI.

Keywords: HCCI, biofuels, hydrogen, emissions control, combustion phasing.

1. Introduction

Internal combustion engines are widely used in transport and power generation, but they face challenges of high emissions and low efficiency. To address these issues, researchers have developed advanced combustion methods. One of the most promising is Homogeneous Charge Compression Ignition (HCCI), which combines features of both spark-ignition and compression-ignition engines.

Homogeneous Charge Compression Ignition (HCCI) is a combustion process in which fuel and air are mixed uniformly before entering the cylinder. Instead of being ignited by a spark plug or direct injection, the mixture auto-ignites when the compression process raises temperature and pressure to the required level. This leads to a simultaneous multi-point ignition throughout the chamber, creating rapid and efficient combustion at lower peak temperatures compared to conventional engines.

Although HCCI-like engines existed in early forms such as hot-bulb engines, modern research into HCCI has expanded since the 1970s with advances in electronic control and simulation. The main advantage of HCCI is that it combines the high efficiency of diesel engines with the low NOx and particulate matter of gasoline engines. Automakers such as Mazda have introduced commercialized variants like Skyactiv-X, which uses Spark Controlled Compression Ignition (SPCCI) to stabilize HCCI in daily driving.

Advantages include very low NOx, negligible soot emissions, and higher efficiency. However, challenges remain: cold start difficulty, limited load range, unstable ignition timing, and higher CO/HC emissions due to incomplete oxidation. Researchers are exploring control strategies such as exhaust gas recirculation, variable compression ratio, and hybridization.

2. Results and Discussion

In recent years, the usage of oil-based fuel keeps increasing like that shown in Fig. 1, and the awareness of environmental protection keep rising.

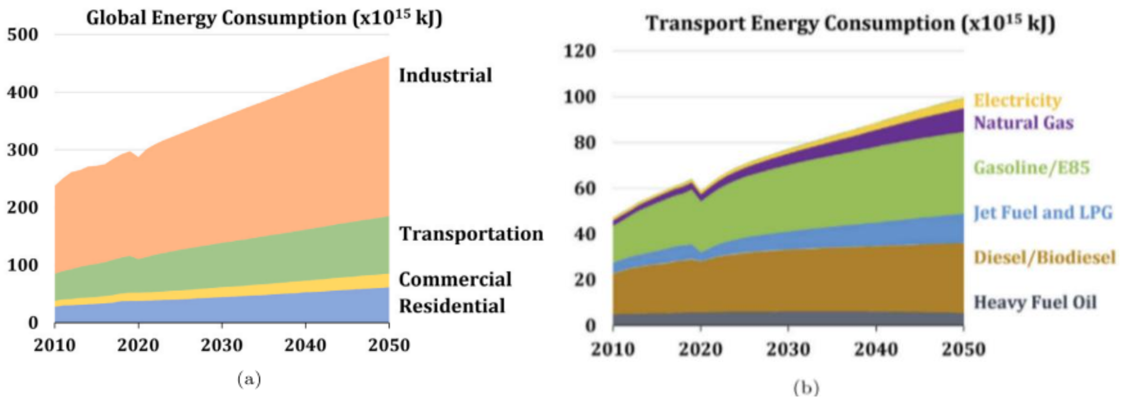


Figure 1. Global energy consumption [1]

2.1. Biomass-Based Mixed Fuels in HCCI Engines

2.1.1. Different kinds of biomass-based mixed fuels

Biomass-derived fuels such as biodiesel, ethanol, and butanol blends are increasingly studied in HCCI mode because of their high oxygen content, which promotes cleaner combustion and reduces soot. There are some widely used kinds of Biomass-Based Mixed Fuels shown in Table 1.

Table 1. Different kinds of Biomass-Based Mixed Fuels [1]

Fuel Blend Composition (vol.%)	Nomenclature
20% Acetone/74% Gasoline/6% EHN	20AGE
20% Diisopropyl Ether/20% Acetone/54% Gasoline/6% EHN	20DAGE
40% Diisopropyl Ether/20% Acetone/34% Gasoline/6% EHN	40DAGE
20% n-Butanol/20% Acetone/54% Gasoline/6% EHN	20BAGE
40% n-Butanol/20% Acetone/34% Gasoline/6% EHN	40BAGE

However, this same oxygen enrichment and variability in volatility affect mixture preparation and ignition timing. Research shows that when the biofuel content in gasoline blends increases, the indicated specific fuel consumption (ISFC) tends to rise, while power output decreases including to Fig. 2.

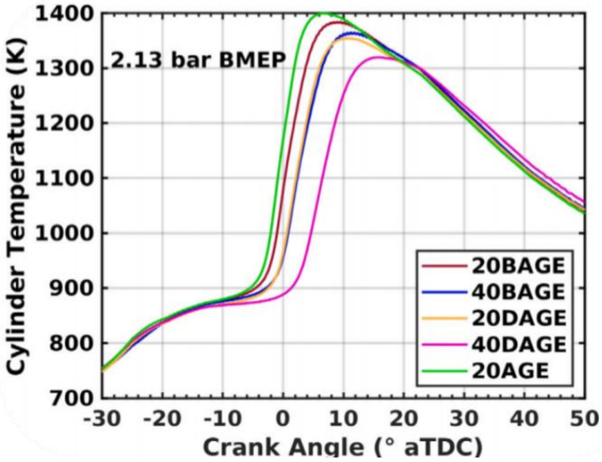
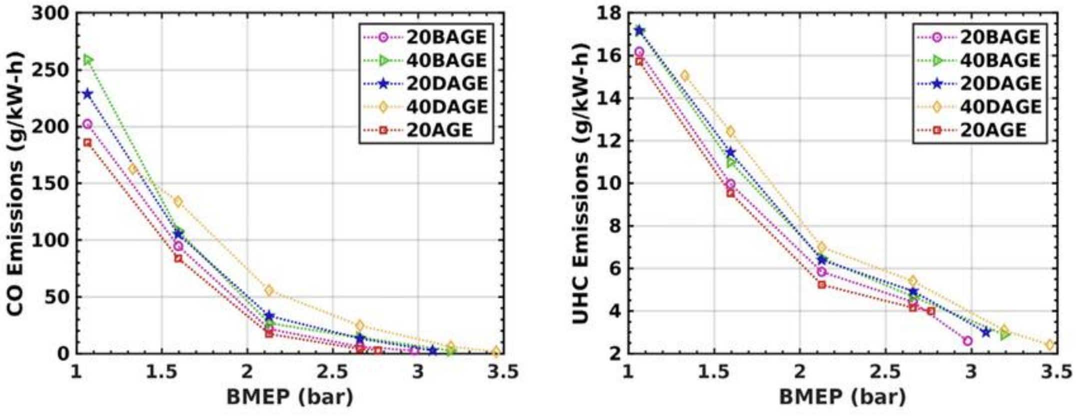
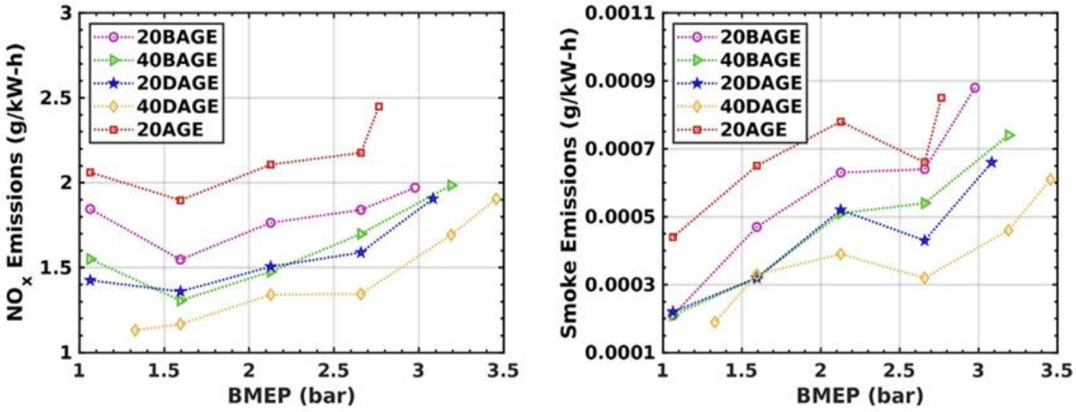


Figure 2. Combustion temperatures of different mixed fuels in the cylinder [1]

At the same time, emissions patterns are logically linked to fuel chemistry: higher oxygen reduces smoke and NOx, but incomplete oxidation of low-volatility biofuels can increase CO and unburned hydrocarbons (HC) including to Fig. 3 [1, 2].



(a) CO Emissions (b) UHC Emissions



(c) NO_x Emissions (d) Smoke Emissions

Figure 3. Emissions from different mixed fuels after combustion [1]

2.1.2. Multi-Biofuel strategies and advantages

To overcome the shortcomings of single-biofuel operation, recent work has proposed dynamic multi-biofuel blending. For instance, combining acetone, diisopropyl ether, and butanol with gasoline not only stabilized combustion but also improved indicated thermal efficiency by up to 1.8×, while lowering NO_x, CO_2, and smoke emissions [1]. The logical advantage here is clear: blending fuels with complementary properties balances volatility, reactivity, and ignition quality, reducing the weaknesses of any one biofuel alone. This demonstrates that biofuels, if used in flexible blends, can be tailored to match HCCI requirements more effectively. Recent comparative experiments show that longer-chain alcohols—n-butanol and isobutanol—offer higher energy density, better blending stability, and superior low-temperature auto-ignition behavior than ethanol in HCCI operation. These properties widen the attainable load range and can moderate pressure rise rates when phasing is properly managed [3].

2.1.3. Challenges and research needs

Although biofuel blends have potential, their chemical and physical properties inevitably lead to a series of issues. Differences in cetane numbers and research octane numbers among various blended fuels make it difficult to control the ignition point accurately and result in unstable engine output loads. Moreover, some organic components in biofuels can react with materials such as plastic and rubber that are widely used in engines, causing durability risks [4]. Since these defects directly lead to the engine's inability to function properly, an important research area is to optimize the blend ratio. Also, introducing additives (such as cetane number improvers), and developing adaptive control strategies to ensure the engine operates properly when using different fuels are highly appreciated.

2.2. Hydrogen Mixed Fuels in HCCI Engines

2.2.1. Combustion behavior and emissions

Hydrogen is often regarded as the ultimate clean fuel for HCCI due to its zero carbon emissions at the point of use. Its logical advantage lies in its fast kinetics and wide flammability limits, which extend ignition boundaries and allow stable combustion at lean equivalence ratios. Studies have confirmed that hydrogen advances ignition timing and lowers intake temperature requirements when blended with other fuels [4, 5]. However, hydrogen's low volumetric energy density displaces air intake, leading to power losses and reduced volumetric efficiency [5]. This creates a trade-off: the cleaner the combustion, the greater the challenge in power density.

2.2.2. Experimental evidence

Experimental research provides consistent insights into hydrogen HCCI operation. At sea level, stable combustion was observed at intake temperatures of 90–110°C with equivalence ratios of 0.16–0.33, achieving thermal efficiencies up to 45% [6]. At high altitudes, however, intake temperature requirements increased by about 100°C, which logically reduced volumetric efficiency and lowered power density [5].

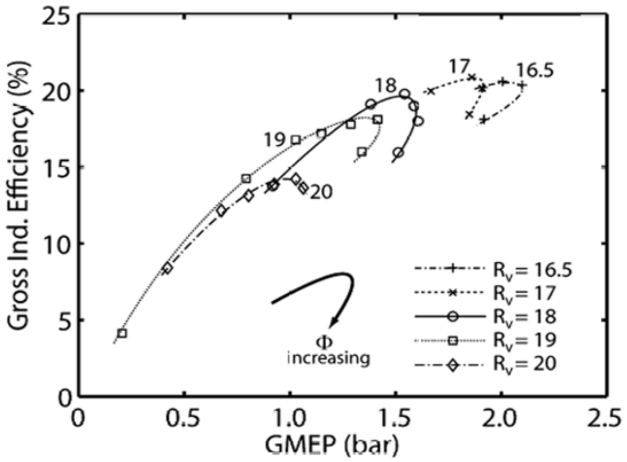


Figure 4. Efficiency of Hydrogen-Mixed Fuels at Different Compression Ratios [4]

Further studies of compression ratio show that increasing the compression ratio reduces the maximum load capacity of the engine including to Fig. 4. This occurs because higher compression leads to earlier ignition and potentially unstable combustion under high load conditions. Conversely, increasing the intake temperature enables the engine to operate across a wider range of equivalence ratios, as well as more flexibility in combustion phasing and mixture preparation. These findings illustrate the balance between thermal efficiency, load limits, and operational stability when hydrogen is used in HCCI engines.[4] Beyond volumetric-efficiency penalties, recent synthesis indicates that hydrogen addition tends to shorten combustion duration, reduce unburned HC, and mitigate knock propensity when appropriately diluted or blended—effects that support stable low-temperature combustion regimes relevant to HCCI and other advanced CI modes [7].

2.3. Possible Solutions to the Challenges at Present

From a control perspective, state-of-the-art strategies for timing and phasing include coordinated intake heating/boost, reactivity control via fuel blending, external/internal EGR, and valve-based control (VVT/VVA); model-based and adaptive feedback controllers using real-time combustion indicators (e.g., CA50) have proven effective at extending the stable HCCI map and limiting PRR, as summarized by Duan et al. [8].

Given that existing alternative fuel HCCI engines generally suffer from low combustion temperatures, poor efficiency (which is additionally due to difficult ignition timing control and easily triggers engine knock), I believe there are the following possible breakthrough paths: using supercharging technology to increase intake pressure, mixing with low auto-ignition temperature fuels (such as diesel), and developing mixed combustion modes such as spark-assisted HCCI.

3. Conclusion

HCCI engines can benefit from both biomass-based and hydrogen fuels. Their advantages and disadvantages seem to follow simple causes. Because biomass-based fuels contain more oxygen, they reduce smoke and Nox emissions. However, incomplete combustion and high blending ratios increases CO and HC as combustion. Hydrogen, on the other hand, can reduce carbon emissions and extend the ignition limits. But cause a suffering in efficiency and the power density. The future of HCCI engines depends on combining these fuel choices with advanced control methods such as variable valve timing, exhaust gas recirculation and hybridization. These methods can directly tie fuel chemistry, engine operation and emission results together and ensure a balance between sustainability, performance and practicality.

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