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Clean combustion of *n*-butanol as a next generation biofuel for diesel engines

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HIGHLIGHTS

- Neat *n*-butanol is studied and applied to replace diesel fuel for clean combustion.
- Emission benefits and technical challenges of *n*-butanol combustion are identified.
- Advanced combustion controls are studied to suit *n*-butanol's distinctive properties.
- An innovative split-combustion strategy is developed to enable full load operation.
- *n*-Butanol combustion delivers diesel-like efficiency with reduced harmful emissions.

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ABSTRACT

This work investigates the applicability of *n*-butanol as a next generation biofuel to replace diesel in compression ignition engines for efficient operation, pollutant mitigation, and CO_2 reduction. A high compression ratio (18.2:1) diesel research engine is configured to run on neat *n*-butanol. Due to the fuel property departure from diesel, *n*-butanol combustion exhibits striking combustion characteristics. Alternative combustion strategies, including via partially premixed compression ignition and homogeneous charge compression ignition, are enabled efficiently owing to distinctive fuel properties of *n*-butanol. The compression ignition of the (partially) premixed *n*-butanol and air mixture is capable of producing diesel-like engine efficiency and significant nitrogen oxide and smoke reductions. As the engine load increases, however, such neat *n*-butanol combustion exhibits rapid burning and suffers abrupt pressure rise. Thereby the engine load is generally limited below 50% of the baseline capability. A split-combustion strategy, which employs multiple event fuel injections, is found to be effective to modulate the noise of *n*-butanol clean combustion, thereby enabling neat *n*-butanol application across the full engine load range.

1. Introduction

Biofuels have raised growing interest in recent years on energy security, greenhouse gas (GHG) mitigation, and socioeconomic harmonization, while the fossil based petroleum fuels remain dominating in the world energy supply [1,2]. Policy-makers are also paying close attention to the use of biofuels; in the United States, the renewable fuel standard is set to sustain the growth of the biofuel industry [3]. Biofuels are among the leading contenders to replace petroleum fuels in the transportation sector for best using the existing powertrain designs and re-fuelling infrastructures. Currently, fuel blends rather than neat biofuels are commonly used for internal combustion engine (ICE) applications, for instance, 5–20% biodiesel (B5-B20) in compression ignition (CI) engines, and 10, 20 and 85% ethanol (E10, E20, and E85) in spark ignition (SI) engines to partially replace diesel and gasoline fuels. The use of 100% biofuels (e.g. B100) is largely in the research and development stage, except for the flex-fuel vehicles capable of running up to 100% ethanol fuel (E100) for Brazilian applications [4]. As suggested by the research findings, the use of biofuels has shown substantial benefits in reducing GHG emissions of the engine systems and on the life-cycle basis [5–10].

In order to circumvent the competition between food and fuel, the next generation biofuels, or the second generation biofuels, are produced from non-food feedstock (e.g. lignocellulose feedstock) and/or food crops that have already fulfilled the food purpose (e.g. vegetable oil waste), which separates them from the first generation biofuels and enables the potential for sustainable, affordable, and environmental friendly fuel supply [11–16]. Butanol is deemed as one of the next generation biofuels for transportation and combustion engine applications [17–19]. Traditionally, bio-

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Nomenclature

ABE	Acetone-Butanol-Ethanol
BMEP	brake mean effective pressure
CA	crank angle
*CA*5	crank angle of 5% total heat release
*CA*50	crank angle of 50% total heat release
*CA*95	crank angle of 95% total heat release
CI	compression ignition
CO	carbon monoxide
COV	coefficient of variation
CO_2	carbon dioxide
DI	direct injection
EGR	exhaust gas recirculation
EOC	end of combustion
FTIR	Fourier Transform Infrared Spectroscopy
FSN	filter smoke number
GHG	green house gas
HC	*hydrocarbon*
HCCI	homogeneous charge compression ignition
HCLD	heated chemiluminescence detector
HFID	heated flame ionization detector
HFRR	high frequency reciprocating rig
HRR	heat release rate
ICE	*internal combustion engine*
IMEP	indicated mean effective pressure
LHV	*lower heating value*
LTC	low temperature combustion
MFB	mass fraction burned
NDIR	non-dispersive infrared detector
NOx	nitrogen oxides
PFI	port fuel injection
ppm	parts per million
PPCI	partially premixed compression ignition
p_{inj}	pressure of injection
p_{int}	pressure of intake
PRRmax	maximum pressure rise rate
SOC	*start of combustion*
SOI	start of injection
TDC	top dead centre
THC	total hydrocarbons
WSD	wear scar diameter

butanol can be synthesized through the Acetone-Butanol-Ethanol (ABE) fermentation process using feedstocks such as cereal grains and sugar, but this process usually suffers from low yields of butanol and receives criticism of causing food shortage [20]. Recent developments in the fermentation process, such as fed-batch, continuous syngas fermentation and immobilized cell fermentation, have substantially improved bio-butanol production with respect to substrate costs, low productivity and downstream process cost and, particularly, the use of non-food feedstock such as lignocellulose materials tackles the confliction with food supply [20–24].

Compared to the most commonly used bio-alcohol fuel, i.e. ethanol, butanol has several advantages for combustion engine applications. Butanol is less corrosive and less prone to water contamination, and thus it is considered as a "drop-in" fuel for the existing fuel distribution infrastructure. Butanol has around 25% higher energy density than that of ethanol, and lower fuel consumption and better mileage can be achieved. In addition, butanol can blend with both gasoline and diesel fuels to be used in SI and CI engines for a wide range of applications.

Butanol possesses similar physical properties to those of gasoline, and many detailed investigations have been performed to study the fuel consumption, combustion characteristics, engine performance, and exhaust emissions of using butanol-gasoline blends on stoichiometric-burn SI engines [25–36]. Applications of butanol-gasoline blends and neat butanol have also been demonstrated on production engines without modifications [37,38]. In these research studies, the similarity in fuel properties is taken as the advantage of butanol to substitute gasoline with minimum compromise on engine performance.

In contrast, the use of butanol in CI engines is often researched to utilize butanol's distinctive fuel properties, e.g. fuel-borne oxygen, for emission reduction of diesel engines. The majority of engine experiments use butanol-diesel blends of different fuel ratios to study the engine performance and exhaust emissions [39–46]. These research studies cover a wide range of diesel engine application and combustion modes, including steady state and transient cycles, naturally aspirated and turbocharged air induction, automotive and stationary engines, and conventional high temperature combustion and premixed low temperature combustion. A consensus is that the addition of butanol noticeably reduces the soot emissions owing to added fuel-borne oxygen and enhanced volatility from butanol. The nitrogen oxides (NOx) in the exhaust emissions can decrease or slightly increase depending on the engine operating conditions, while the use of exhaust gas recirculation (EGR) can effectively suppress the NOx emissions.

Another butanol application in CI engines is the recent development of dual fuel engine operations. In butanol-diesel dual fuel combustion, the two fuels are delivered individually instead of using fuel blends, and the fuel blending occurs inside the cylinder [47–51]. A secondary intake port fuel injection (PFI) is added to a direct injection (DI) diesel engine, and butanol is therefore delivered via PFI similar to its application in SI engines but usually ignited via the direct injection of diesel. A major advantage of dual fuel combustion is that the fuel ratio can be adjusted on the fly by controlling the fuelling rate of each fuel, rather than a fixed fuel ratio as the fuel blend in the fuel tank. In general, these dual fuel test results show the benefits of adding an oxygenated fuel to diesel; the better mixing and oxygen availability result in soot reduction and thus permit higher EGR ratios to reduce NOx emissions. The dynamic control of fuel blending ratio offers additional flexibility in combustion control to better accommodate different engine operating conditions.

Despite the butanol fuel blends and dual fuel applications are actively investigated, a relatively limited number of studies have been performed to explore the neat butanol application that completely replaces diesel in CI engines. The combustion characteristics and fuel spray of neat *n*-butanol have been investigated through fundamental studies in constant volume chambers that simulate diesel combustion environments [52–54]. Engine tests have also shown encouraging potentials of neat *n*-butanol to produce comparable engine efficiency to its diesel counterpart while emitting substantially lower NOx and smoke emissions [49,55–58]. In the meantime, these research studies also manifest the engine load limitations of butanol combustion in diesel engines. A primary advantage of diesel engines is its high power density, and thus the use of a biofuel to replace diesel becomes less attractive if the fuel change results in a large degradation in engine performance and power density. Therefore, the authors intend to evaluate the benefits and challenges of neat *n*-butanol application