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# Comparison of Butanol/n-Heptane to PRF Blended Fuels in HCCI Engines

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## 1. Abstract

Butanol and n-heptane fuel blends are compared to Primary Reference Fuel blends of iso-octane and n-heptane by measuring 98 steady-state HCCI combustion operating points. The volume percentage of the blended fuel with n-heptane and fuel equivalence ratio are varied while all other engine parameters are held constant. The experimental results show that HCCI operation is possible with Butanol blends up to 48.5% and with iso-octane blends up to 63%. Higher indicated thermal efficiencies when running the engine on blends of butanol are obtained compared to the PRF blends and the Butanol blends have a later start of combustion and a slower rate of heat release compared to the PRF blends. Operating points that have the same thermal efficiency but a lower volume percent of butanol compared to iso-octane have been found and this could be an advantage since a smaller amount of secondary fuel would be required.

## 2. Introduction

The low PM and NOx emissions and fuel flexibility of HCCI engines combined with its fuel-flexibility make them a promising alternative to conventional Spark Ignition (SI) or Compression Ignition (CI) engines [1]. Fuels with a wide range of octane or cetane number can be burned in HCCI engines. Oxygenated fuels have become more important for internal combustion engines in recent years [2]. Butanol when produced from plants and bio-products is a renewable fuel and has physical and chemical properties closer to that of gasoline than methanol and ethanol fuels and can be used without modification in engines designed for gasoline [3]. This makes Butanol a viable alternative renewable fuel that can help decrease the demand for fossil based fuels.

Butanol can be produced by fermentation of biomass by the acetone-butanol-ethanol process [4]. Butanol production from biomass and agricultural byproducts is more efficient than ethanol or methanol production [4]. The transportation of Butanol via pipeline is relatively straight forward compared to Ethanol, which is fully miscible in water [5], and Butanol is much less corrosive on metal parts when compared to Ethanol [3].

The effects of Butanol blends on engine performance are detailed in [3, 5, 6, 7, 8]. Compared to Ethanol blended gasoline, Butanol blended gasoline contains about 15% more energy density [5]. For CI engines, fuel atomization characteristics are improved because of lower viscosity, density, and surface tension of the Butanol blend compared to diesel fuel [7].

Despite the comprehensive research on Butanol fuel in SI and CI engines, relatively little research has been done to investigate Butanol blends in HCCI engines [8]. The purpose of this paper is to explore the feasibility of utilizing blends of Butanol and n-Heptane in an experimental HCCI engine. Engine performance characteristics such as Indicated Mean Effective Pressure (IMEP) and indicated thermal efficiency ($\eta_{th}$) are determined and compared for the two fuel blends to show that it is possible to get higher thermal efficiency and IMEP when the engine is fueled with Butanol and n-Heptane fuel blends.

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### 3. Engine Setup

An experimental single cylinder Ricardo Hydra Mark III engine fitted with a VVT Mercedes E550 cylinder head is depicted in Figure 1 and the configuration of the engine is shown schematically in Table 1. Two separate fuel systems with 3-bar fuel pressure are used with fuel injection timing set to inject on closed intake valves. One fuel injector is used to inject n-Heptane and the other is used to inject either Butanol or Iso-octane. The separate flow rate control of each of these two fuels allows any desired volume percentage of the blended fuel with n-heptane to be obtained. Both injectors are aimed directly at the back of the intake valves. The fresh intake air entering the engine is first passed through a laminar air-flow meter for flow rate measurement. Then, a supercharger driven by a variable speed electric motor adjusts the intake manifold pressure and a 600W electrical band-type heater regulates the intake mixture temperature to a desired value. Finally the exhaust gases exiting the cylinder are sampled for emission analysis. A 5-gas emissions test bench is used to collect emissions data but the results are not reported here.

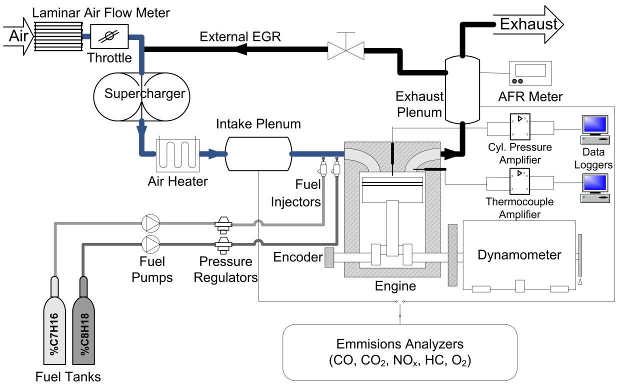



Figure 1: Single cylinder engine testbench schematic

Table 1: Single cylinder engine configuration and operating conditions

| Parameters | Values |
|---|---|
| Bore × Stroke [mm] | 97 × 88.9 |
| Compression Ratio | 12 |
| Number of Valves | 4 |
| IVO, IVC [aBDC] | 151°, 21° |
| EVO, EVC [aBDC] | −100°, 130° |
| **Variables** | **Values** |
| Engine speed [rpm] | 1021 |
| Intake manifold temperature [$^oC$] | 80 - 82 |
| Intake manifold pressure [kPa] | 122 - 125 |
| EGR [%] | 0 |
| $T_{coolant}$ [$^oC$] | 69 - 71 |
| BVP [%] | 0 - 48.5 |
| PRF [%] | 0 - 63 |

Table 2: Engine Operating Conditions

| Working Points | BVP [a] | $\phi$ | $\eta_{th}$ [b] | IMEP [kPa] |
|---|---|---|---|---|
| A | 38% | 0.357 | 33.64% | 3.06 |
| B | 22% | 0.325 | 31.45% | 2.76 |
| C | 22% | 0.366 | 31.81% | 3.12 |
| **Working Points** | **PRF [c]** | $\phi$ | $\eta_{th}$ | **IMEP [kPa]** |
| D | 37% | 0.355 | 32.47% | 3.05 |
| E | 22% | 0.323 | 32.45% | 2.78 |
| F | 45% | 0.376 | 32.47% | 3.22 |

[a] Butanol Volume Percentage of Butanol n-heptane blend
[b] Indicated Thermal Efficiency
[c] Primary Reference Fuel. Iso-octane volume in n-heptane blend

The engine out Air Fuel Ratio (AFR) is measured by an ECM AFRecorder 1200 UEGO and used to calculate equivalence ratio ($\phi$). The intake temperature is measured with 2°C resolution using a K-type thermocouple positioned in the intake manifold before the charge enters into the cylinder. The exhaust temperature is measured using a 1/32″ sheathed J-Type thermocouple which is placed in the exhaust as close as possible to the exhaust valve. Crank Angle measurement with 0.1° resolution is done using a BEI optical encoder connected to the crankshaft at the front the engine. Measurement of the cylinder pressure is done using a Kistler water-cooled ThermoCOMP (model 6043A60) piezoelectric pressure sensor that is flush mounted in the cylinder head.

The experimental conditions of the 98 steady-state points used in this study are summarized in Table 1. The amount of injected fuel and the fuel volume percent of Butanol in n-heptane (BVP) or iso-octane in n-heptane (PRF) is varied while all other engine variables are kept constant. Pressure traces from 300 consecutive engine cycles with 0.1 Crank Angle (CA) degree resolution are recorded for each engine test. Six steady state points, denoted A through F, are selected for further examination and are listed in Table 2. The start of combustion in HCCI is determined using the third derivative of the pressure trace criteria [9]. The Rassweiler method [10] is used to calculate $CA_{50}$ which is the crank angle for 50% burnt fuel. The net heat release rate is determined using a standard heat release method [11] that applies a first law analysis on the engine charge assuming ideal gas properties. Other engine variables are measured at a constant sample rate of 100Hz during each test.

## 4. Results

Using experimental cylinder pressure traces with varying BVPs and PRFs, the HCCI combustion performance measures of: IMEP, $\eta_{th}$, Rate of Pressure Rise (dP/dCA) and Heat Release Rate (HRR) are compared. Combustion performance analysis for each of 300 pressure cycles is averaged. All the variables in Table 1 are kept constant except the volume percentage of the blended fuel with n-heptane (BVP or PRF) and the fuel equivalence ratio ($\phi$). As shown in Figure 2, it is possible to reach higher IMEPs with BVP blends compared to PRF blends. The lower heating value of Butanol is about 75% of iso-octane while the density of the later is about 75% of the former. Therefore the amount of energy which is injected in each cycle hardly changes when switching between BVP blends and PRF blends [3]. Since, Butanol contains oxygen atoms, the stoichiometric AFR of Butanol is lower than gasoline so it is possible to inject more fuel to increase engine power [3]. In addition, the latent heat of Butanol is approximately 2.3 times that of iso-octane so the evaporation of Butanol can reduce the mixture temperature resulting in higher volumetric efficiency and power output [3].

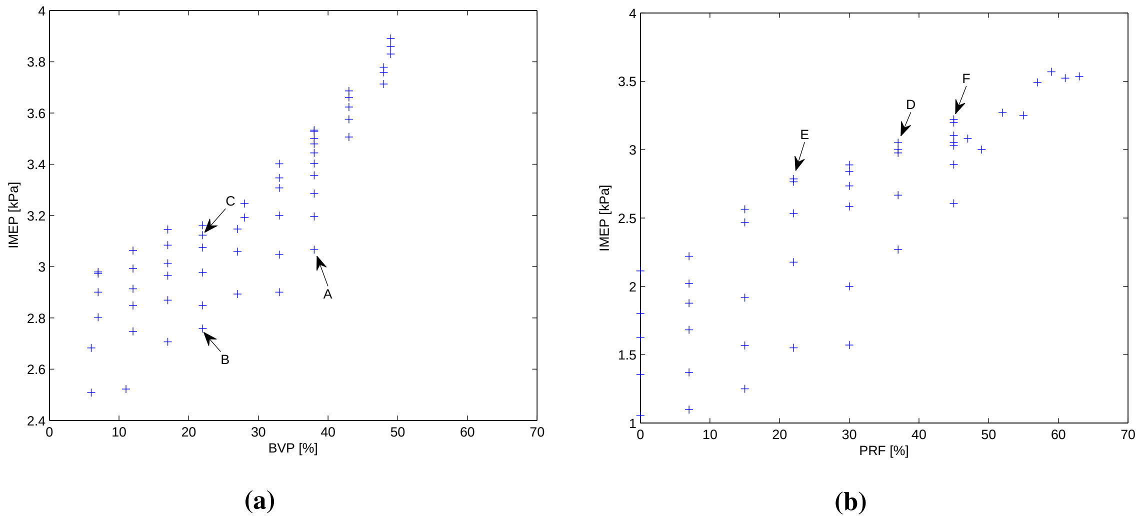
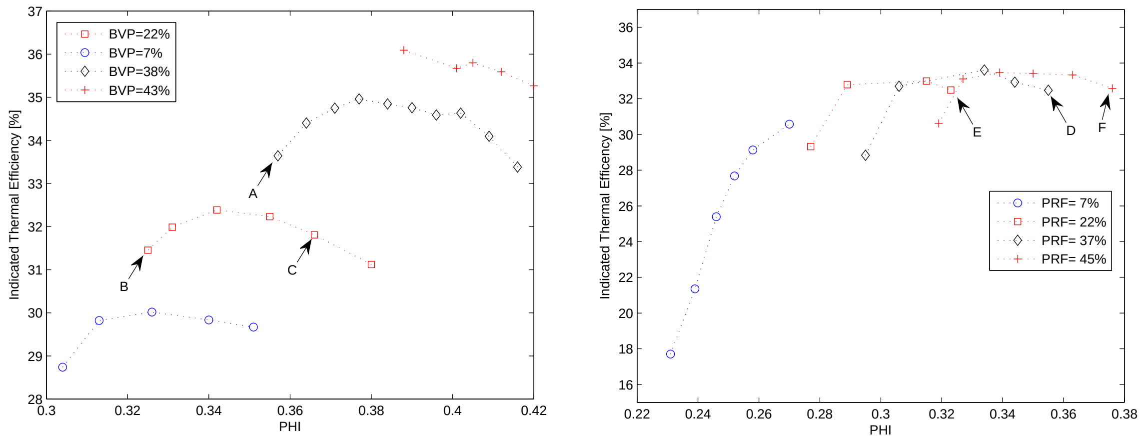



Figure 2: IMEP versus (a) BVP and (b) PRF (A through F correspond to engine operating points listed in Table 2)

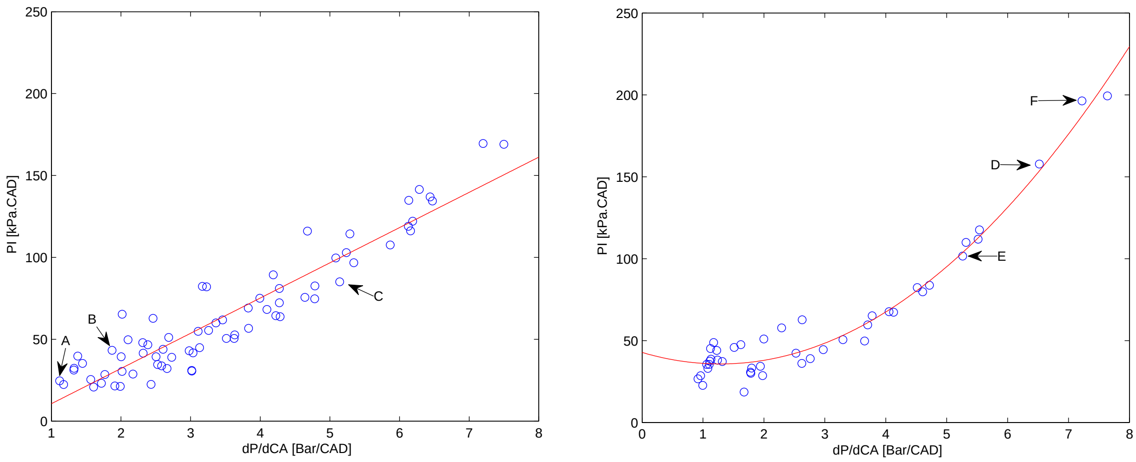
Indicated thermal efficiency ($\eta_{th}$) as a function of equivalence ratio ($\phi$) for 4 BVP and PRF blends are shown in Figure 3. Higher thermal efficiencies with BVP blends compared to PRF blends are obtained. One reason is that Butanol has a higher Octane number, hence BVP blends would have stronger knocking resistance making it possible to inject more fuel per cycle to get higher thermal efficiencies . To study knock of the engine when burning BVP or

PRF blends the knock indexes are calculated based on [12, 13]). In-cylinder pressure signals are band pass-filtered with a fourth order filter and the normalized cut-off frequency of 20/360. The filtered pressure signal is subtracted from unfiltered pressure signal and integrated over the combustion period and the integrated values are the Pressure Intensity (PI) [12].




**(a)** **(b)**

Figure 3: Variation of indicated thermal efficiency versus equivalence ratio at different (a) BVPs and (b) PRFs. (A through F correspond to engine operating points listed in Table 2)

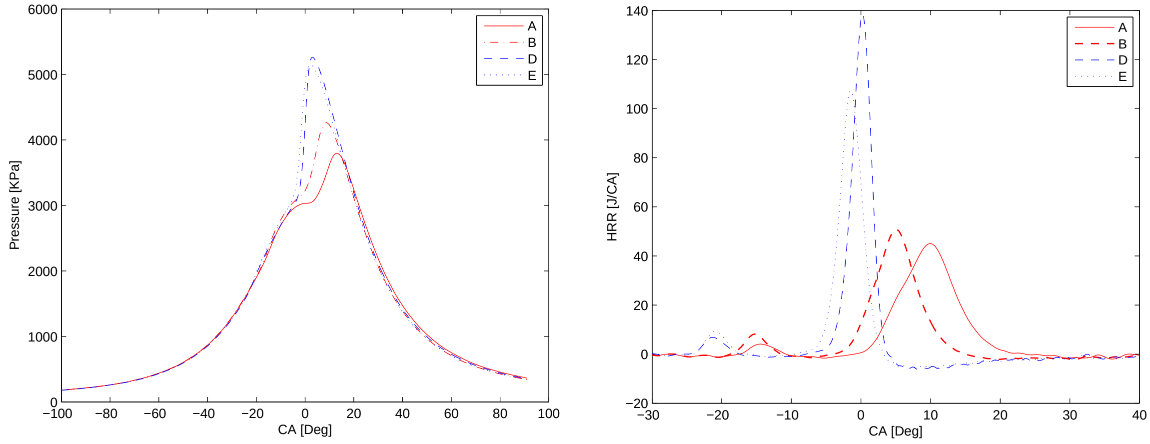



**(a)** **(b)**

Figure 4: Pressure Intensity (PI) versus maximum rate of pressure rise at different (a) BVPs and (b) PRFs. (A through F correspond to engine operating points listed in Table 2)

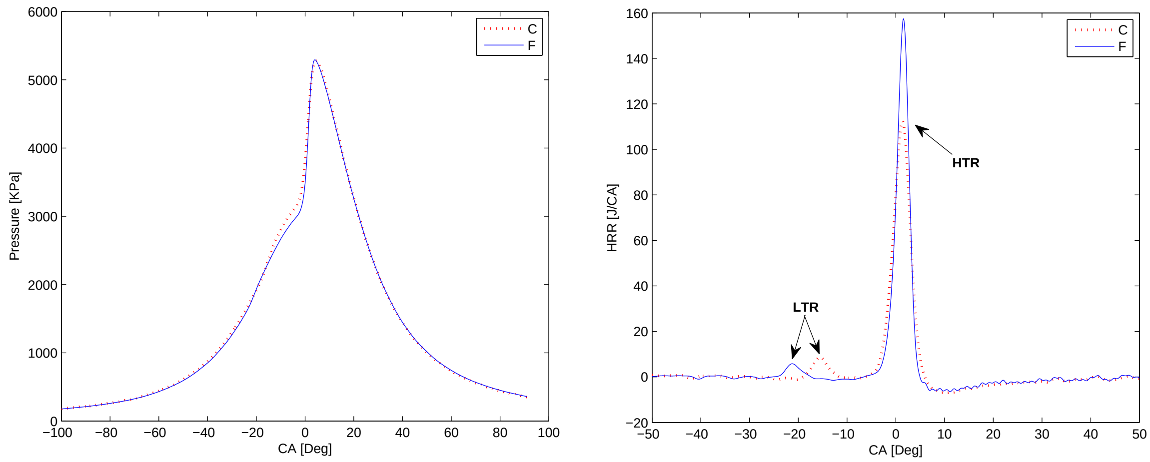
The lower air/fuel mixture temperature at the end of compression for BVP blends compared to PRF blends lead to longer ignition delay [8]. When the combustion occurs late, the rate of pressure rise is lower as the majority of the combustion occurs during the expansion stroke. Since the majority of combustion happens during expansion stroke, the Pressure Intensity (PI) [12] is also lower as shown in Figure 4. Thus, the possibility of knock is lower when engine is running on BVP blends compared to PRF blends.

Two pairs of engine operating points (A,D) and (B,E) (see Table 2) with the same fuel blend ratios (BVP=PRF) and the same equivalence ratios ($\phi_A$=$\phi_D$, $\phi_B$=$\phi_E$) are used to compare the fuel blends . Figures 5 shows the cylinder pressure trace and heat release rate for these engine operating points (A,B,D,E). Each point also has the same values of thermal efficiency ($\eta_{th,A}$=$\eta_{th,D}$, $\eta_{th,B}$=$\eta_{th,E}$) as well as IMEP as tabulated in Table 2. The peak pressure in the case of Butanol is less than iso-octane and the knock intensity is lower. The main reason for lower peak pressure and slower heat release rate for BVP blends is the later CA50. As can be seen in Figure 5(b) both Low Temperature Reactions (LTR) and High Temperature Reactions (HTR) occur earlier for iso-octane as discussed earlier.




**(a)** **(b)**

Figure 5: (a) Cylinder pressure versus Crank Angle (b) Heat release Rate versus Crank Angle (A through D refer to engine operating points in Table 2)




**(a)** **(b)**

Figure 6: (a) Cylinder pressure versus Crank Angle (b) Heat release Rate versus Crank Angle (C and F refer to engine operating points in Table 2)

Figures 6 compares the cylinder pressure trace and heat release rate for two engine operating points (C,F in Table 2) which have the same CA50 and injected fuel energy. It is found that they have similar values of thermal efficiency and IMEP, but the possibility of knock in BVP is lower as shown in Figure 4. Additionally, BVP=22% for case C is less than half of the PRF=45% for case F which means a smaller amount of Butanol is needed compared to iso-octane. In Figure 6(b) both these fuels exhibit a Low Temperature Reaction (LTR) and a High Temperature Reaction (HTR) as the small and large bump respectively. As seen in Figure 6(b) the crank angle between LTR and HTR is smaller for the BVP case. It is also possible to control the crank angle between LTR and HTR as well as rate of heat release by modulating the amount of butanol which is added to the blended fuel [8].

### 5. Summary and Conclusions

A comparison of the combustion characteristics of Butanol in n-Heptane versus iso-octane in n-Heptane is performed on an experimental HCCI engine. The volume percent of Butanol and iso-octane and the equivalence ratio ($\phi$) are varied while all other engine inputs are held constant. For this engine and the conditions studied, HCCI operation is possible with Butanol blends up to BVP$\leq$48.5% and with iso-octane blends up to PRF$\leq$63%. Compared to PRF blends it is possible to reach higher IMEPs and indicated thermal efficiencies when the engine is running on blends of Butanol and n-Heptane. In this case, start of combustion occurs later and rate of heat release is slower. At a constant engine thermal efficiency and IMEP, the knock intensity is lower for Butanol blends. It is possible to reach higher thermal efficiencies and IMEPs with less Butanol in the fuel blend. Further studies regarding the engine out emissions when the engine is running on BVP blends are needed.

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