

An Experimental Study on the Use of Butanol or Octanol Blends in a Heavy Duty Diesel Engine

Tankai Zhang, Karin Munch, and Ingemar Denbratt
Chalmers Univ of Technology

ABSTRACT

Global warming driven by “greenhouse gas” emissions is an increasingly serious concern of both the public and legislators. A potentially potent way to reduce these emissions and conserve fossil fuel resources is to use n-butanol, iso-butanol or octanol (2-ethylhexanol) from renewable sources as alternative fuels in diesel engines. The effects of adding these substances to diesel fuel were therefore tested in a single-cylinder heavy duty diesel engine operated using factory settings. These alcohols have better calorific values, flash points, lubricity, cetane numbers and solubility in diesel than shorter-chain alcohols. However, they have lower cetane numbers than diesel, so either hydrotreated vegetable oil (HVO) or Di-tertiary-butyl peroxide (DTBP) was added to the diesel-alcohol mixtures to generate blends with the same Cetane Number (CN) as diesel. Blends containing 10 and 20% of n-butanol or iso-butanol, or 30 % octanol were tested at four operating points from the European Stationary Cycle. The same engine settings were used in all cases.

The average engine performance in tests with the blends was similar to that achieved with pure diesel but the blends generated less cycle-to-cycle variation. The brake thermal efficiency was similar for all the fuels but the brake specific fuel consumption was slightly higher for the blends due to their lower calorific value. Because of their oxygen content, the blends produced much lower emissions of soot and carbon monoxide than were achieved with diesel. Blends yielded slightly higher NO_x emissions than pure diesel and all the fuels produced similar hydrocarbon emissions. Possibly because of its branched molecular structure, the iso-butanol blends yielded slightly higher soot emissions than the n-butanol blends. Because HVO contains no aromatics, its addition to fuel blends reduced soot emissions. Overall, these results confirm the substantial potential of renewable longer-chain alcohols as components of blended diesel fuels.

CITATION: Zhang, T., Munch, K., and Denbratt, I., "An Experimental Study on the Use of Butanol or Octanol Blends in a Heavy Duty Diesel Engine," *SAE Int. J. Fuels Lubr.* 8(3):2015, doi:10.4271/2015-24-2491.

INTRODUCTION

Emissions from fossil fuel-burning internal combustion engines are a cause of major concern around the world due to their effects on health and the climate. The EU has committed to reduce overall greenhouse gas emissions from its 28 Member States by 20% relative to 1990 levels and to increase the proportion of energy generated from renewable resources within the transportation sector to 10% by 2020 (with the overall share of energy generated from renewable sources rising to 20%). By 2030, the intent is to reduce greenhouse gas emissions by at least 40% relative to the 1990 level, and for renewable sources to account for at least 27% of all energy consumption [1,2]. The partial replacement of fossil fuels with alcohols could potentially help in achieving these goals.

Biofuels such as alcohols can be derived from grain starches and sugar crops but also from non-food biomass [3]. The partial replacement of fossil fuels with alcohols and the development of improved methods for alcohol production from new sources can

reduce greenhouse gas (GHG) emissions on a Well-to-Wheels (WTW) basis. For example, replacing fossil fuels with ethanol produced from sugar or crops reduces WTW typical GHG emissions by 32-69%. If the ethanol is produced from wheat straw or waste wood instead, the reduction in WTW typical GHG emissions rises to 80-87%[4]. Other alcohols produced from inedible feedstocks such as methanol or butanol can also be used as fuels, reducing life cycle GHG emissions by 70% to 90% [4,5].

The potential for using ethanol as a replacement for diesel or a component of blended fuels based on diesel has been investigated extensively [6, 7, 8, 9]. The hydrophilicity of ethanol makes it insoluble in diesel and it is necessary to add an emulsifier to ethanol-diesel blends, which is a major problem. The physical properties of butanol and octanol (without special indication octanol mentioned in this study is 2-ethylhexanol) make them more suitable than methanol or ethanol as alternative fuels for diesel engines. Table 1 shows the properties of selected alcohols and fossil diesel.

Table 1. Properties of alcohols and diesel [3,10,11,12,13]

	Methanol	Ethanol	Iso-butanol	N-butanol	Octanol	Diesel
Oxygen percent (Wt.%)	49.93	34.73	21.62	21.62	12.31	-
Density (g/ml)	0.787	0.785	0.802	0.810	0.832	0.837
Calorific values (MJ/kg)	20.1	26.9	33.17	33.21	38.4 ^a	42.8
Cetane number	3.8	5-8	<15	17-25	23	52
Flash point (°C)	12	13	28	35	75	74
Boiling point(°C)	65	79	108	118	195 ^a	210-235
Lubricity (μm)	1100	1057	-	590	-	315
Vaporization latent heat	1109	904	566	582	562 ^a	270
Solubility in water	Miscible	Miscible	Immiscible	Immiscible	Immiscible	Immiscible

^a Value quoted is for 1-octanol

Both butanol and octanol have excellent solubility in diesel. Butanol also has a higher flash point than ethanol, which is very important in fuel storage and distribution. The flash point of octanol is even higher than that of diesel.

Increasing the length of an alcohol's carbon chain reduces its latent heat of vaporization but increases its calorific value and CN, making its properties more similar to those of diesel [14]. Alcohols have a lower energy density than diesel, which complicates their use in diesel engines. However, the output of a diesel engine using a fuel blend comprising 30% butanol in diesel was within 96% of that achieved with pure diesel. The use of diesel-alcohol blends increases the efficiency of combustion, partly compensating for the lower volumetric energy content [15].

To meet increasingly strict emissions regulations, it is important to reduce soot and NOx emissions generated during fossil fuel combustion. Unlike conventional diesel, alcohols contain oxygen; consequently their combustion is generally slightly leaner than that of diesel and causes the formation of localized 'leaner zones', especially in fuel-rich regions of the burning spray. This reduces soot emissions in both light- and heavy-duty engines. Diesel-butanol blends also

tend to have slightly lower combustion temperatures than those achieved with pure diesel due to butanol's lower calorific value and higher heat of evaporation. Consequently, NOx emissions from engines using diesel/butanol blends are slightly lower than those achieved with pure diesel [16,17]. The use of butanol/diesel blends thus effectively suppresses soot formation while maintaining NOx emissions [18].

This study aims to investigate butanol/diesel and octanol/diesel blends in a single-cylinder heavy duty diesel engines based on a production engine with factory calibration. The CN is decreased by raising the proportion of alcohol in the diesel/alcohol blend. If the CN of the blend is low enough that the ignition delay is a bit longer than the injection duration, low temperature combustion (LTC) can be achieved, further reducing soot and NOx emissions [19,20]. However, the long ignition delays caused by using fuels with low CN values are known to produce combustion behaviour [21,22] and thermal characteristics [23] that differ from those achieved with pure diesel. The CN of butanol/diesel blends can be increased to meet the EN590 diesel fuel standard by adding a high CN fuel such as HVO or small volumes of an ignition improver like DTBP.

Table 2. Properties of components and mixtures

	Diesel	N-butanol	Iso-butanol	Octanol	HVO	DTBP	Density	CN
	vol.%	vol.%	vol.%	vol.%	vol.%	mg/kg	kg/l	-
Diesel	100	-	-	-	-	-	0.8370	52
N-butanol	-	100	-	-	-	-	0.8136	< 20
Iso-butanol	-	-	100	-	-	-	-	< 20
Octanol	-	-	-	100	-	-	0.8363	23.2
HVO	-	-	-	-	100	-	0.7799	75.1
nBu10H	70	10	-	-	20	-	0.8223	50.6
nBu20H	40	20	-	-	40	-	0.8082	50.3
nBu10D	90	10	-	-	-	600	0.8338	51.3
nBu20D	80	20	-	-	-	12000	0.8311	~49
isoBu10H	60	-	10	-	30	-	0.8159	51.7
isoBu20H	20	-	20	-	60	-	0.7950	52.5
isoBu20D	80	-	20	-	-	12000	0.8294	49.0
Oct30	70	-	-	30	-	6000	0.8358	49.9



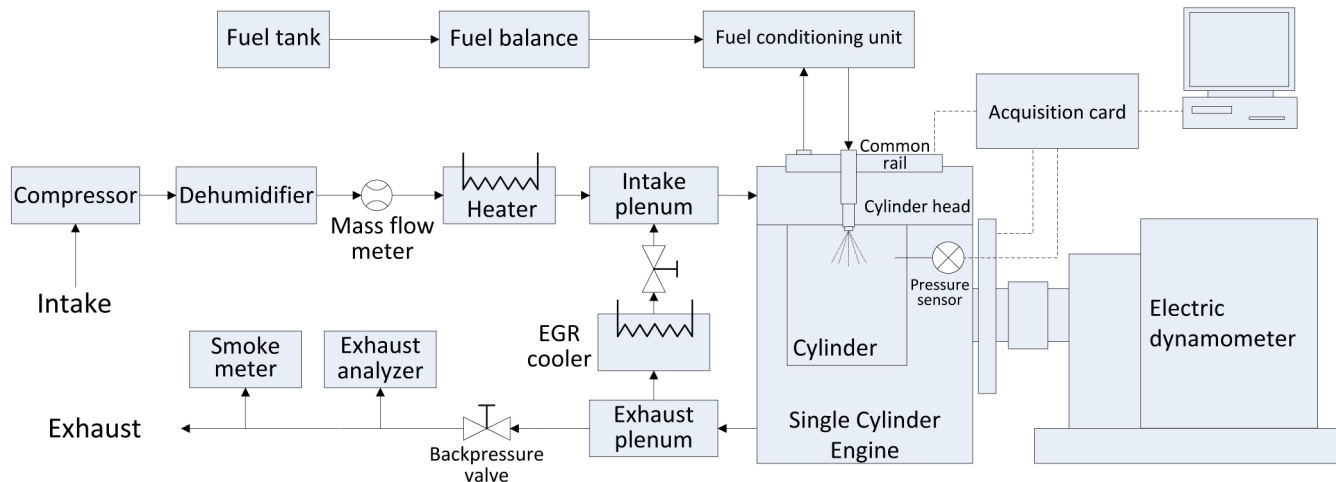


Figure 1. Schematic of the experimental setup

The physical properties of n- and iso-butanol are similar, but the intermediates and emissions generated during their combustion differ due to their molecular structures [24]. Therefore, both isomers were examined in this work. Octanol was also considered to assess engine performance when using an even longer chain alcohol in diesel blends.

EXPERIMENTAL APPARATUS AND METHODS

Fuel Preparation

The diesel fuel used in this study is VSD10 diesel, which meets the EN590 standard but contains no biofuel (FAME). All experiments with “pure diesel” were conducted using only VSD10 with no added alcohol. N-butanol, iso-butanol and octanol were blended with diesel together with either HVO or DTBP to increase the blends' CN. N-butanol, iso-butanol and octanol were supplied by Perstorp AB in Sweden. HVO is refined from vegetable oils and animal fats, and consists almost exclusively of straight chain and branched paraffins. It is completely devoid of aromatics and sulfur, which reduces emissions [25,26]. The CN of HVO is much greater than that of diesel fuel, so it can be added to diesel/alcohol blends to compensate for the alcohol's low CN. The HVO used in this work was produced by Neste. DTBP is a widely used ignition improver that increases a blend's CN even when added in very small volumes [27].

The CN of the different blends was determined using a cooperative fuel research (CFR) engine that complies with the ASTM D-613 standard, which is a widely accepted method for determining ignition delay and CN values. The CFR engine is a standard single cylinder engine with a combustion chamber that allows the compression ratio to be adjusted continuously during testing. The reference fuels are tested under identical conditions after a sample fuel test. CN values for the blends used in this work are shown in Table 2.

Pure diesel was used as the reference fuel. To match the CN of diesel (52), DTBP or HVO were added to the eight different alcohol/diesel blends. For fuels with CN values between 48 and 52, the reproducibility of CFR engine test results ranges from 3.8 to 4.3, and all the tested blends are in this range. The blends are named systematically: the first part denotes the alcohol used (isoBu = iso-butanol, nBu = n-butanol, Oct = octanol), the second denotes the proportion of alcohol in the blend (10, 20, or 30 for 10%, 20%, and 30%, respectively), and the last part denotes the additive used (H for HVO, D for DTBP). Thus, nBu10H denotes a blend of 10% n-butanol in diesel with added HVO.

Test Engine and Test Facility

Experiments were conducted on a 2 liter AVL 501 single cylinder heavy duty diesel engine equipped with a common rail injection system and a cylinder head and piston based on the Volvo Powertrain D12C engine. Table 3 shows the engine's specifications. The test engine uses the Delphi F2 distributed pump diesel common rail system, enabling the use of higher (up to 270 MPa) and more stable injection pressures.

Table 3. Engine specifications

Engine type	AVL 501 Single cylinder
Bore	131 mm
Stroke	150 mm
Valves	4
Connecting rod length	260 mm
Compression ratio	17:1
Fuel injection system	Common rail
Injection pressure	180 MPa
Nozzle	5 holes

Figure 1 shows a schematic of the heavy duty engine test bed. An AVL 733S fuel balance was used to measure the fuel mass flow rate, and the fuel was passed through a conditioning unit before delivery to the pumping injector. A Kistler 7061B pressure sensor, a Kistler 3066A01 piezo amplifier and an Osiris data acquisition system were used to acquire cylinder pressure data at 0.1 crank angle resolution for 100 cycles. Exhaust gas recirculation (EGR) was adjusted by controlling the backpressure with a valve in the exhaust pipe. The recirculated exhaust gases were cooled by a water cooler before being mixed with the compressed intake air whose humidity and temperature were controlled.

The concentrations of unburned hydrocarbons (HC), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO₂) and oxygen (O₂) in ppm (parts per million, by volume) in the exhaust gas were measured using an AVL AMA i60 exhaust measuring system. HC and NO_x emissions were measured as wet gases, so no wet correction was required for these species. Soot emissions measurements were performed with an AVL 415 Smoke Meter. The filter smoke number (FSN) was measured based on the blackening of filter paper through which raw exhaust gas was passed. The soot concentration (mg/kg) in the exhaust was calculated as below:

$$\text{Soot} = \frac{1}{0.405} \times 4.95 \cdot \text{FSN} \cdot e^{0.38 \times \text{FSN}} \times \frac{1}{1.169}$$

Test Conditions

Four operating points from the European Stationary Cycle were chosen: A25, B50, C75 and B75. B50 was chosen as the reference point.

The first experimental runs were performed with pure diesel, followed by the different fuel blends listed in Table 2. In each fuel test, the tested fuel was performed several times under the reference point B50 to get the error bars in the plots. When changing from one fuel blend to another, the fuel balance was emptied and filled with the new fuel twice, after which the engine was operated for at least 30 min with the new fuel at the reference operating point to consume residual fuel in the fuel line before starting the experimental runs with the new blend. After each blend test, a reference test was conducted using pure diesel fuel at the B50 operating point to ensure that the engine's performance was not changing in a way that affected the reproducibility of the results obtained.

To investigate the scope for using butanol/diesel blends in a factory setting diesel engines, all of the tested engine settings (see Table 4) were based on the engine's factory calibration of the Volvo Powertrain D12C engine, and all the different blends were tested using identical engine settings.

The EGR rates used in this work were 20% to 100% greater than those of the factory settings to maintain the specific NO_x emissions at 1.8 g/kWh when using pure diesel, which is just below the 2.0 g/kWh Euro V limit. The same EGR rates were used for all blends, as shown in Table 4. The EGR value was calculated as follows:

Table 4. Engine settings

Operating conditions	unit	A25	B50	C75	B75
Torque	Nm	78.0	145.9	186.0	219.5
Speed	rpm	1200	1500	1800	1500
Injection pressure	MPa	180	180	180	180
Injection duration	μs	660	1000	1300	1400
Start of injection	CAD BTDC	4.52	7.80	4.50	9.40
EGR	%	29.0	25.9	21.9	24.1
Boost	mbar	256	940	1735	1464

$$\text{EGR} = \frac{CO_{2 \text{ intake}}}{CO_{2 \text{ exhaust}}} \times 100\%$$

The concentrations of CO₂ were the values relative to the fresh intake air.

RESULTS AND DISCUSSION

Engine Performance

Figure 2 shows the average rate of heat release from 100 engine cycles using different fuel blends. Previous studies [16,28,29] using butanol/diesel blends without cetane number improver yielded rate of heat release curves for blended fuels that differed from those for pure diesel. In contrast, rate of heat release of the blends obtained in this work were very similar to those for pure diesel. Alcohol/diesel blends with the same CN number as diesel yielded very similar rate of heat release curves to pure diesel, regardless of the additive (HVO or DTBP) used to raise the blends' CN number. Because the injection timing was the same and ignition delays were close for each fuel at same operating point, the extent of premixed combustion for the blends was very similar to that for pure diesel.

Figure 3 shows the maximum in-cylinder pressure generated using pure diesel and the studied blends as a function of the crank angle at the different operating points. As expected, all of the fuels have similar peak cylinder pressures and locations of maximum pressure. However, some small differences of maximum pressure location of the different fuels can be seen at A25 and C75. This is probably because the cylinder pressure curves at A25 and C75 are quite flat around the peak pressure, so small differences in the maximum pressure can generate large deviations in location. In addition, under most operating conditions the maximum pressure for pure diesel fuel was slightly lower than that for the blends, which because the combustion of the blends is more intense than that of diesel fuel [30].