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# Effects of biobutanol and biobutanol–diesel blends on combustion and emission characteristics in a passenger car diesel engine with pilot injection strategies

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ABSTRACT

In this study, we investigated the effect of biobutanol and biobutanol–diesel blends on the combustion and emission characteristics in a four-cylinder compression ignition engine using pilot injection strategies. The test fuels were a mixture of 10% biobutanol and 90% conventional diesel (Bu10), 20% biobutanol and 80% diesel (Bu20), and 100% diesel fuel (Bu0) based on mass. To study the combustion and emission characteristics of the biobutanol blended fuels, we carried out experimental investigations under various pilot injection timings from BTDC 20° to BTDC 60° with constant main injection timing. As the butanol content in the blended fuel increased, the experimental results indicated that the ignition delay was longer than that of diesel fuel for all pilot injection timings. Also, the indicated specific fuel consumption (ISFC) of the blended fuels was higher than that of diesel at all test conditions. However, the exhaust temperature was lower than that of diesel at all injection timings. Nitrogen oxide (NOx), carbon monoxide (CO) and soot from Bu20 were lower than those from diesel fuel at all test conditions and hydrocarbons (HC) were higher than that from diesel.



## 1. Introduction

To meet the growing worldwide emission regulations and address the issues associated with fossil fuels, a lot of research on energy development, mitigation technologies, and cleaner fuel is being conducted. Alternative fuels, including dimethyl ether, alcohol fuels, and biodiesels have been actively investigated from an emissions point of view [1–4]. The uses of alcohol fuel in a compression ignition engine are divided into two cases: (i) ethanol or ethanol–gasoline injection into the intake manifold with ignition by diesel injection as an ignited fuel, and (ii) compression ignition of an ethanol–diesel blended fuel injected into the combustion chamber.

In an example of the first type of engine mentioned above, Sarjovaara and Larmi [5] investigated an ethanol–gasoline blend (E85) used as a primary fuel with diesel as an ignition source in a dual-fuel combustion engine. In their design, the E85 fuel was injected into the intake manifold, and the mixture was ignited using diesel fuel injection near the top dead center. They achieved high E85 rates up to 89% based on energy content under medium load conditions. Their results revealed that the E85 increased carbon monoxide (CO) and un-burned hydrocarbon emissions, but decreased nitrogen oxide (NOx) emission. Also, smoke emissions were low in all cases, and smoke emissions at a high E85 rate decreased to near zero.

As an example of the second type of engine mentioned above, Hasimoglu et al. [6] reported the effects of injection timing on the performance of a single cylinder diesel engine fueled with different diesel–ethanol fuels. In their study, the fuel mixtures were prepared by addition of ethanol to diesel fuel at ratios of 5%, 10%, and 20% by volume. A maximum power showed at 2400 rpm with a 5% diesel–ethanol fuel mixture at an injection advance of 35° of crank angle (CA). Also, they investigated the effects of injection timing on the torque and brake-specific fuel consumption in a test engine with different diesel–ethanol blends.

Many other studies have examined ethanol fuel and ethanol–diesel blends for diesel engines with dual fuel systems [7–11]. The lower heating value (LHV) of ethanol and butanol are 26.87 MJ/kg and 33.4 MJ/kg, respectively [1,4]. The LHV of ethanol fuel is equivalent to about 61% of conventional diesel fuel. Therefore, large amounts of butanol fuel are required to obtain the same power output for butanol operation; however, less butanol is needed than ethanol because the LHV of butanol fuel is 18.46% higher than that of ethanol fuel [12]. In addition, the latent heat from the evaporation of ethanol is 840 kJ/kg, and that value is

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**Nomenclature**

| | |
|---|---|
| ATDC | after top dead center (°) |
| Bu | butanol |
| BTDC | before top dead center (°) |
| CA | crank angle |
| CN | cetane number |
| COV | coefficient of variance |
| CO | carbon monoxide (g/kW h) |
| DME | dimethyl ether |
| HC | hydrocarbon (g/kW h) |
| IMEP | indicated mean effective pressure (MPa) |
| ISFC | indicated specific fuel consumption (g/kW h) |
| IS | indicated specific |
| LHV | lower heating value (MJ/kg) |
| $N$ | total number of measurements |
| NOx | nitrogen oxides (g/kW h) |
| $P$ | pressure (MPa) |
| $P_{inj}$ | injection pressure (MPa) |
| ROHR | rate of heat release (J/deg) |
| ROPR | rate of pressure rise (MPa/deg) |
| $t_m$ | main injection timing |
| $t_p$ | pilot injection timing |
| $V$ | volume ($m^3$) |
| $X_{avg}$ | ensemble average |

*Greek symbols*

| | |
|---|---|
| $\kappa$ | specific heat ratio |
| $\theta$ | crank angle (°) |

larger than the 585 kJ/kg of butanol fuel [6]. Many oxygenated fuels, such as ethanol, butanol, and biodiesel can be produced from plant resources. The combustion of ethanol and butanol fuels derived from plant resources do not produce additional $CO_2$ emissions because plants absorb carbon dioxide during growth. In the case of various blends of butanol and diesel fuel, smoke and CO emissions can be reduced because the high oxygen content of n-butanol leads to improved soot oxidation in the cylinder, and it decreases the smoke density from the engine [13]. Furthermore, butanol has a higher cetane number (CN) of 25 and a higher energy content than ethanol fuel [14].

Butanol can be produced by fermentation of biomass, such as corn, algae, and other plant materials containing cellulose. Butanol is a primary alcohol with a molecular formula of $C_4H_9OH$, and it is therefore an oxygenated fuel. Butanol has advantages over both ethanol and methanol as an alternative fuel for combustion engines. As mentioned above, many studies have investigated ethanol or ethanol blended fuels, but few studies have examined the application of butanol to diesel engines as an alternative fuel [16–18]. Zheng et al. [15] investigated the effects of neat n-butanol fuel on clean combustion in a diesel engine. Their results showed that low temperature combustion resulted in ultra-low NOx and near-zero emissions by using n-butanol fuel. The current literatures for diesel–butanol blending effects on performance and emissions in a diesel engine is limited compared to gasoline engine applications [19–23]. Siwale et al. [19] investigated the effects of the butanol–diesel blend on thermal efficiency and brake fuel consumption in a turbo-charged CI engine. In their study, fuel consumption and thermal efficiency were reported the influence of butanol blending ratios. To understand the effect of n-butanol–diesel blend on the emission of a DI diesel engine, Choi et al. [20] studied that the n-butanol blend showed the increase in NOx emission compared with the neat diesel fuel, and the case of 20% butanol resulted in THC and CO emissions increased. Also, blending ratio of 5% butanol reduced the PM and nanosized particulates. In addition, the investigations of butanol addition to biodiesel–diesel blend have been investigated by many researchers [21–24]. These works conducted the impacts of ternary blends and environmental problems.

The one major drawback of ethanol fuel is that it mixes poorly with diesel fuel. Solving this problem requires the use of a suitable emulsifier or co-solvents in the blending process. On the other hand, butanol fuel can be mixed with petroleum diesel without phase separation. Moreover, compared to ethanol fuel, butanol has a lower ignition temperature, lower volatility, and a higher flash point. Therefore, biobutanol would be a more suitable alternative fuel than ethanol. Also, if alcohol-based biofuels (bioethanol, biobutanol, methanol, etc.), are mixed with diesel fuel at a low mixing ratio, they can be applied without changing the fuel supply system in a diesel engine.

In this study, the effects of biobutanol and biobutanol–diesel blends on the combustion and emission characteristics of a four-cylinder passenger car diesel engine were experimentally analyzed under constant injection pressure and various pilot injection timings. The combustion effects of biobutanol and its blends on gas pressures, heat release, and emissions reduction characteristics were compared with those of conventional diesel under various biobutanol blending ratios and injection timings. In order to investigate the effects of engine load on the exhaust emissions, the combustion characteristics, maximum combustion pressure, IS-NOx, IS-Soot, IS-CO, and IS-HC emissions were analyzed according to the various load conditions and pilot injection timings for various butanol blended diesel fuels.

## 2. Experimental setup and procedure

### 2.1. Experimental setup and test fuels

The physical and chemical properties of test fuels and blended ratios of biobutanol are listed in Table 1 and Table 2, respectively. In this investigation, test fuels were prepared using the following blending ratios: a mixture of 80% biobutanol and 20% diesel fuel (Bu20), a mixture of 90% biobutanol and 10% diesel fuel (Bu10), and 100% conventional diesel (Bu0). The experimental apparatus consisted of a four-cylinder diesel engine, a combustion analyzer system, a dynamometer with a control system, and an exhaust emissions analyzer, as illustrated in Fig. 1. The engine used in this study is based on a four-cylinder direct injection diesel engine for a passenger car with a displacement volume of 1.582 L, a compres-

**Table 1**
Fuel properties of butanol and diesel [27,31].

| Item | Butanol | Diesel |
|---|---|---|
| Molecular formula | $C_4H_9OH$ | $C_{12}$–$C_{22}$ |
| Molecular weight | 74 | 180–220 |
| Oxygen content (%) | 21.6 | 0 |
| Density at 20 °C (kg/m$^3$) | 810 | 825 |
| Kinematic viscosity at 40 °C (mm$^2$/s) | 2.63 | 2.42 |
| Cetane number | ~25 | ~50 |
| Bulk modulus of elasticity (bar) | 15,000 | 16,000 |
| Boiling point (°C) | 118 | ~180–360 |
| Latent heat of evaporation (kJ/kg) | 585 | 250 |
| Lower heating value (MJ/kg) | 33.1 | 43 |
| Stoichiometric air–fuel ratio | 11.2 | 15 |