EXPERIMENTAL INVESTIGATION ON CYCLIC VARIABILITY, ENGINE PERFORMANCE, AND EXHAUST EMISSIONS IN A DIESEL ENGINE USING ALCOHOL-DIESEL FUEL BLENDS

by

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This paper investigates the impacts of using n-butanol-diesel fuel and ethanol-diesel fuel blends on engine performance, exhaust emission, and cycle-by-cycle variation in a Diesel engine. The engine was operated at two different engine speed and full load condition with pure diesel fuel, 5% and 10% (by vol.) ethanol and n-butanol fuel blends. The coefficient of variation of indicated mean effective pressure was used to evaluate the cyclic variability of n-butanol-diesel fuel and ethanol-diesel fuel blends. The results obtained in this study showed that effective efficiency and brake specific fuel consumption generally increased with the use of the n-butanol-diesel fuel or ethanol-diesel fuel blends with respect to that of the neat diesel fuel. The addition of ethanol or n-butanol to diesel fuel caused a decrement in CO and NO_x emissions. Also, the results indicated that cycle-by-cycle variation has an increasing trend with the increase of alcohol-diesel blending ratio for all engine speed. An increase in cyclic variability of alcohol-diesel fuel blends at low engine speed is higher than that of high engine speed.

Key words: *Diesel engine, cyclic variation, n-butanol, ethanol, exhaust emission, engine performance*

Introduction

Diesel engines are considerably used in many applications due to higher effective efficiency and durability. However, burning of fossil fuels in Diesel engines produces emissions that have serious effect on both human health and environment. Also, increasing energy demand and depletion of petroleum resources in the world have recently become important issue. The solution of these problems is to reduce the consumption of petroleum derived fuels and develop Diesel engine technology such as exhaust gas after-treatment, exhaust gas re-circulation, and multiple injection method [1, 2]. Alternative fuels are considered a potential substitute to fossil fuels because they reduce greenhouse effect and energy dependence. Among the alternative fuels, alcohols are an attractive fuel. In addition, alcohols like butanol and ethanol which made from biomass can play a critical role in helping to support farming industry [3, 4]. Ethanol, commonly known as ethyl alcohol is a colorless, volatile, flammable,

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and biodegradable fuel. It is produced by fermentation of vegetable materials, such as wheat, corn, and sugar [5]. Butanol is a four-carbon atom alcohol that occurs in four isomeric structures: n-butanol (normal butanol), 2-butanol (secondary butanol), i-butanol (iso-butanol), and t-butanol (tert-butanol). All four isomers have the same formulae and the same amount of heat energy but have different molecular structures that impact their properties. Like ethanol, butanol can be produced from renewable agricultural products [6]. Butanol has several favorable properties for Diesel engines compared to that of ethanol. For example, the tendency of water absorption is lower, and therefore n-butanol has lower corrosion problems compared to ethanol. Also n-butanol can be stocked in a fuel tank for a longer time. The n-butanol also has higher kinetic viscosity than ethanol. Consequently, better wear characteristics between moving parts in a fuel injection system may be expected [7]. In addition, cetane number which is the most important property for Diesel engine and heating value of butanol is higher than that of ethanol. Cyclic variability has long been recognized as a limiting factor in engine performance, fuel efficiency, and emissions [8]. Fuel type has big impact on cycle-by-cycle variations due to differences in physicochemical properties such as cetane number, volatility, viscosity, and latent heat of vaporization. Thus, cyclic variability has received considerable attention for higher efficient combustion and lower emissions. Some researchers have already studied engine performance and exhaust emissions of alcohol-diesel fuel blends and cyclic variability. Bilgin *et al.* [9] determined the best blending ratio of ethanol and the compression ratio of the engine for the best efficiency. The experimental study was performed on single cylinder, 4-stroke, and water cooled Diesel engine for three different percentage of ethanol in diesel (E2, E4, and E6) and three different compression ratio (19, 21, and 23). They reported that a blend of 4% by volume of ethanol with diesel was determined the optimum percentage ratio. Also, the optimum efficiency was achieved at the compression ratio of 21 with an increment ratio over 3.5%. Rakopoulos *et al.* [10] conducted the study on a six cylinder, turbocharged and direct injection Mercedes-Benz engine for effects of using blends of ethanol with diesel fuel (E5 and E10) on the engine performance and exhaust emissions. The results show that the NO_x and CO emissions slightly decrease with an increase in ethanol. Also, the addition of ethanol to diesel fuel caused an increment in both brake specific fuel consumption (BSFC) and thermal efficiency. Dogan [11] studied the effect of n-butanol and diesel fuel blend on the engine performance and exhaust emissions of a single cylinder, 4-stroke, and naturally aspirated high speed Diesel engine. The experimental test results showed that smoke opacity, NO_x, and CO emissions decreased while HC emissions increased with the use of n-butanol. In addition, both brake thermal efficiency and BSCF increased with increasing amount of n-butanol in the fuel mixture. Sahin and Aksu [12] conducted an experimental investigation the effects of using n-butanol diesel fuel blends on the engine performance and exhaust emissions of a four cylinder, 4-stroke, water-cooled, turbocharged, and common-rail injection Renault automotive Diesel engine. They observed that BSFC was decreased for B2 fuel blend while BSFC was increased for B4 and B6 fuel blends. Smoke as lower for all fuel blends when compared to diesel fuel. The NO_x emission decreased for B2. However, NO_x generally increased for B4 and B6. Ali *et al.* [13] researched the cyclic variations of biodiesel-diesel fuel blend with butanol additive. The experimental study was conducted on a Mitsubishi 4D68 multi-cylinder, natural aspirated, and water-cooled Diesel engine. Engine cyclic variations were evaluated by using both wavelet power spectrum and coefficient of variation. Minimum value of COV_{IMEP} was attained for 30% biodiesel-diesel fuel blend (contains 30% biodiesel and 70% diesel fuel in volume basis). Also, the addition of butanol to this fuel blend caused an increment in cyclic variability. Selim [14] studied cyclic variations of a single cylinder, 4-stroke and naturally aspirated dual fuel engine. In this study, liquefied petroleum gas and methane were used as the main fuel while diesel fuel was used as pilot fuel. The engine was operated at different fuel, engine load, compression ratio, pilot fuel injection timing, pilot fuel mass, and engine speed. The study showed that cyclic variability in dual fuel engine is higher than the corresponding diesel fuel case. As seen in the aforementioned studies, significant amount research has been carried out on cycle by cycle variation of dual fuel engine [15, 16] or Diesel engine fueled with biodiesel [17-19]. However, there are fewer studies of cyclic variability of ethanol or n-butanol diesel fuel blend directly. Therefore, present study focuses on determining the cyclic variation of Diesel engine fueled with both ethanol and n-butanol and makes comparison between these fuels. In addition, more insights and better understanding of ethanol-diesel fuel and butanol-diesel fuel blends on the engine performance, exhaust emissions and combustion stability will be gained by the presented study.

Experimental study

The experimental studies were performed on a naturally aspirated, 4-stroke, air-cooled, single-cylinder, and direct injection Hatz 1B40 Diesel engine which is loaded by an electrical dynamometer. The details of the test engine are given in tab. 1 and schematic diagram of the test set-up used in the experiments is presented in fig. 1.

Table 1. Specifications of the test engine

Engine type	Air cooled, 4-stroke CI engine
Cylinder number	1
Bore	88 mm
Stroke	76 mm
Connecting rod length	124 mm
Engine capacity	462 cm^3
Compression ratio	20.5
Absolute maximum power	7.3 kW at 3600 rpm

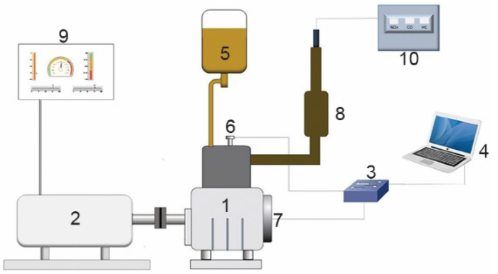

Figure 1. Schematic diagram of the experimental system; *1 – engine, 2 - dynamometer, 3 – cycle analyzer, 4 – computer, 5 – fuel tank, 6 – pressure sensor, 7 – shaft encoder, 8 – exhaust pipe, 9 – control panel and display, 10 – exhaust analyzer*

The CO and NO_x emissions were measured with BİLSA MOD 2210 exhaust gas analyzer. The accuracies of CO and NO_x measurement are within ±0.001% vol. and 1 ppm, respectively. In-cylinder pressure is measured by piezo-electric pressure transducer connected to the relevant amplifier. The 50 sequential combustion cycles were recorded for each fuel blend due to determine cyclic variability. Mineral diesel fuel, 5% v/v, 10% v/v ethanol-diesel fuel blends (E5 and E10, respectively), and 5% v/v, 10% v/v n-butanol diesel fuel blends (B5 and B10, respectively) were used in order to investigate the impacts of alcohol blending on engine performance, exhaust emissions, and combustion cyclic variation, with the engine working at two engine speed (1000 and 2000 rpm) and full load conditions. Properties of diesel fuel, n-butanol and ethanol are shown in tab. 2. Alcohols as fuels can not be directly used in a Diesel engine due to low cetane number. In order to use alcohol in Diesel engines, different methods, namely dual injection, alcohol fumigation, alcohol-diesel fuel blend is employed [2]. In this study, ethanol and n-butanol were used by blending it with conventional diesel fuel. Experiments have been performed after operating the engine until steady-state condition

Table 2. The main properties of diesel fuel and n-butanol

	Diesel fuel	n-Butanol	Ethanol
Chemical formula	$C_{14}H_{24}$	C_4H_9OH	C_2H_5OH
Molecular mass [kgkmol^{-1}]	192.346[c]	74.123[c]	46.069[c]
Density [kgm^{-3}]	834.5[a]	813.6[a]	796.0[a]
Lower heating value [kJkg^{-1}]	42,600[b]	33,600[b]	27.423[b]
Cetane number	59.8[a]	8.7[a]	5.05[a]
Kinematic viscosity, at 40 °C, [mm^{2}s^{-1}]	2.938[a]	2.268[a]	1.092[a]
Flashpoint [°C]	60.5[a]	37.5[a]	13[a]
Composition, mass [%]	c'= 0.874	c'= 0.648	c'= 0.522
	h'= 0.126	h'= 0.136	h'= 0.131
		o'= 0.216	o'= 0.347

[a] Measured in laboratory, [b] Calculated from Mendeleyev formula, [c] Calculated from chemical formula

Table 3. Accuracies of the measurements and the uncertainty values

Measurements	Accuracy
Engine speed	±1 rpm
Engine torque	±0.1 Nm
Temperature	±0.1 °C
Pressure	±1 mbar
Calculated results	Uncertainty [%]
Effective efficiency	±1.05
Brake specific fuel consumption	±1.02

is attained. Before starting the engine with new fuel blend, fuel from the previous experiment was completely discharged from fuel tank. Uncertainty analysis was to confirm the accuracy of the experiments. In this study, uncertainties of the effective efficient and BSFC values were determined by the method developed by Kline and McClintock [20]. Table 3 shows the accuracies of the measurements and the uncertainties of engine performance parameters.

Cyclic variability

Observation of indicator diagram shows that each cycle is found to follow a different path. It knows as cyclic variability or cycle-by-cycle variation. Cyclic variability is measured by indicated mean effective pressure (IMEP), 10% mass fraction burn (MFB), 50% MFB, 90% MFB, maximum cylinder pressure, crank angle at which this maximum pressure occurs, maximum cylinder rate of pressure rise, crank angle at which this maximum cylinder rate of pressure rise, maximum heat release rate, and maximum mass burning rate, *etc.* [21, 22]. Diesel engines, due to the nature of dominantly non-premixed CI combustion, where fuel injection primarily governs air-fuel mixing and thus combustion, have lower cyclic variations compared to spark ignition engines [23]. However, it has been growing interest in cyclic variation of Diesel engine for meeting rigorous imposed emissions regulations. One of the most important methods is to evaluate of cycle-to-cycle variation is to calculate the coefficient of variation in IMEP. Also, some alternative techniques, such as continuous wavelet transform, short time Fourier transform, mean instantaneous frequency, proper orthogonal decomposition have been attracting attention [21]. In general, combustion variability is created by variations in in-cylinder gas motion due to turbulence and swirl, amount of fuel, air and residual burned mass variability and finally differences in mixture preparation prior to combustion [17, 22]. In addition, fuel type has big impact on cycle-by-cycle variations due to differences in physicochemical properties such as cetane number, volatility, viscosity, and latent heat of vaporization. Fuel blends which lower cetane number cause higher cyclic variation which lead to lower engine performance and higher exhaust gas emissions [6, 23]. If cyclic variations can be reduced, engines have lower emission, higher efficiency. Therefore, the issue of controlling these variations is becoming more urgent. Cycle-by-cycle variation is evaluated for 50 consecutive cycles with five different fuel; namely pure diesel, E5, E10, B5, and B10 at two engine speeds of 1000 and 2000 rpm and full load condition. The IMEP is a well-accepted combustion parameter used in evaluating cyclic combustion variability because it reflects the extensive pressure information of the entire cycle. Thus, coefficients of variation in IMEP were used to investigate the cyclic variability for this study and COV_{IMEP} is the standard deviation in IMEP divided by the mean IMEP and defined, respectively:

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{IMEP} 100 \tag{1}$$

$$\sigma_{IMEP} = \sqrt{\frac{\sum_{i=1}^{n}\left(\overline{IMEP} - IMEP_i\right)^2}{n-1}} \tag{2}$$

$$\overline{IMEP} = \frac{1}{n}\sum_{i=1}^{n} IMEP_i \tag{3}$$

Results and discussions

Engine performance

Figure 2 shows the variation of BSFC with the engine speed. The results indicated that addition of n-butanol or ethanol to diesel fuel caused an increase in BSFC. However, BSFC is lower at 2000 rpm for E5 when compared to neat diesel fuel or n-butanol. In general, the BSFC is found to be higher for n-butanol compared to that of ethanol. Among the alcohol-diesel fuel blends, the highest BSFC was obtained from B10 at 1000 rpm. The lower calorific value of ethanol (27,423 kJ/kg) and n-butanol (33,600 kJ/kg) are lower than that of diesel fuel (42,600 kJ/kg), therefore, more fuel is needed to get a certain power output, which increases the BSFC. However, improvement of the combustion by oxygen enrichment decreases the BSFC [24]. The lower calorific value is more effective than oxygen enrichment. This trend is also supported by other research [4, 24, 25]. Concerning the effective efficiency with the alcohol-diesel fuel blends against the pure diesel fuel case, slightly higher effective efficiency is observed with the increment of alcohol ratio in the blend. This increment is given in fig. 3. Similar trends were also observed by previous studies [4, 24]. Ethanol or n-butanol, due to lower cetane number, lead to higher percentage of *constant volume* combustion, and to the lower average cylinder gas tempera-

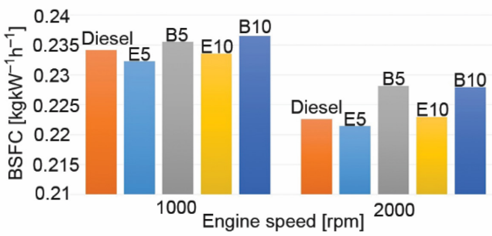

Figure 2. The BSFC *vs.* engine speed

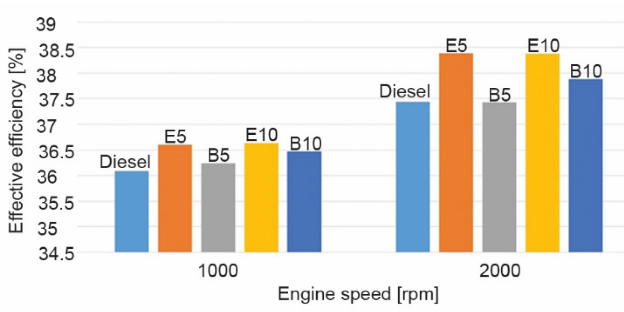

Figure 3. Effective efficiency *vs.* engine speed

tures) and to *leaner* combustion if compared to diesel fuel. Thus, these alcohols have higher premixed combustion part. Consequently, effective efficiency is enhanced [26].

Exhaust emissions

The formation of NO_x highly depends from temperature of the gas inside the cylinder, the oxygen concentration, and residence time for the reaction to take place [3, 27]. The NO_x emissions are shown fig. 4. It can be observed from this figure that NO_x emission is lower compared to neat diesel fuel for all alcohol-diesel fuel blends. Similar trends were also observed by previous studies [4, 24, 28, 29]. The low cetane number (leads to an increase of ignition delay and heat release), and the large amount of oxygen in the alcohol blends produce high gas temperature within the cylinder [30]. However, high latent heat of evaporation which absorbs heat from surroundings when it vaporizes thus, it cools the cylinder charge and low heating value cause low gas temperature within the cylinder. As a result, combustion temperature lowering parameters is more dominant than combustion temperature increasing parameters. The incomplete combustion causes CO emission, and tends to increase with insufficient oxygen [3, 31]. Figure 5 illustrates the variation of CO emissions with the engine speed. The results indicated that CO emissions are significantly decreased with the use of ethanol or n-butanol in the fuel blends for all engine speed. Alike results were reported in the relevant literature [4, 25, 28].

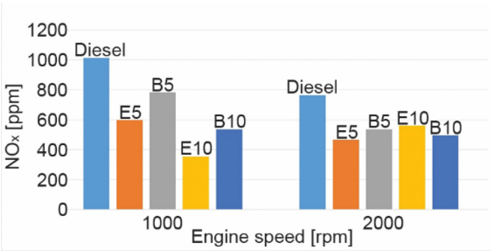

Figure 4. The NO_x emissions *vs.* engine speed

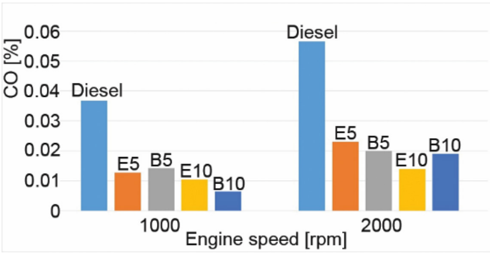

Figure 5. The CO emissions *vs.* engine speed

Cyclic variation

The variation in the value of COV_{IMEP} with respect to different ethanol-diesel and n-butanol diesel fuel blends at two engine speeds is shown in fig. 6. It can be observed from this figure that value of COV_{IMEP} has an increasing trend with the increase of alcohol-diesel blending ratio. But, there is a different result at B5 fuel blend operation. Cyclic variability of B5 fuel blend decreased at 2000 rpm. In general, neat diesel fuel run stable than that of the ethanol or n-butanol diesel fuel blends. This may be attributed to lower cetane number which leads to prolong ignition delay. It can also be observed that an increase in cyclic variability of alcohol-diesel fuel blends at low engine speed is higher than that of high engine speed. Also, COV_{IMEP} values exhibit a decreasing trend according to an increment in the engine speed for each fuel. This may be due to process of air-fuel mixing is improved due to the fact that higher piston velocities make the air swirling more efficient. In conclusion, it was found that both fuel type and engine speed affected the combustion cyclic variation. The COV_{IMEP} was observed as 1.883, 2.959, 2.079, 4.201, and 2.562 for pure diesel fuel E5, B5, E10, and B10, respectively at 1000 rpm. In the case of the 2000 rpm engine speed, COV_{IMEP} was observed as 1.414, 2.144, 1.393, 2.111, and 1.430 for pure diesel fuel E5, B5, E10, and B10, respectively.

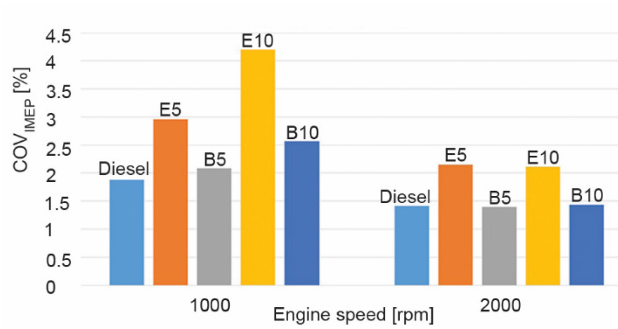

Figure 6. The COV_{IMEP} *vs.* engine speed

Conclusions

Present paper investigates the impacts of using ethanol-diesel fuel and n-butanol diesel fuel blends on the engine performance, exhaust emissions, and cycle-to-cycle variation. The experimental studies were performed on a naturally aspirated, 4-stroke, aircooled, single-cylinder, and direct injection Hatz 1B40 Diesel engine with the engine working at two engine speed (1000 and 2000 rpm), and full load conditions. Mineral diesel fuel, two kinds of diesel fuel-ethanol (E5 and E10) and two kinds of diesel fuel-butanol (B5 and B10) were used for this study. The conclusions are as follows.

- Addition of n-butanol or ethanol to diesel fuel caused an increment in BSFC. Also, the BSFC is found to be higher for n-butanol compared to that of ethanol.
- Effective efficiency increased with increasing amount of n-butanol or ethanol in the fuel mixture.
- The NO_x emissions decreased with the addition of n-butanol or ethanol to diesel fuel.
- The CO emissions are significantly decreased with the use of ethanol or n-butanol in the fuel blends.
- The COV_{IMEP} value has an increasing trend with the increase of alcohol-diesel blending ratio.
- An increase in cyclic variability of alcohol-diesel fuel blends at low engine speed is higher than that of high engine speed.
- The COV_{IMEP} values show a diminishing trend according to an increment in the engine speed for each fuel.

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Nomenclature

B5 – 5% n-butanol and 95% diesel fuel in volume basis
B10 – 10% n-butanol and 90% diesel fuel in volume basis
c' – mass percent of carbon
E5 – 5% ethanol and 95% diesel fuel in volume basis
E10 – 10% ethanol and 90% diesel fuel in volume basis
h' – mass percent of hydrogen
o' – mass percent of oxygen

v/v – volume/volume

Acronyms

BSFC – brake specific fuel consumption
CI – compression ignition
COV – coefficients of variation
IMEP – indicated mean effective pressure
MFB – mass fraction burn

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