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Prediction of cyclic variability in a diesel engine fueled with n-butanol and diesel fuel blends using artificial neural network

Samet Gürgen [a], Bedir Ünver [b], İsmail Altın [c,*]

[a] Department of Naval Architecture and Marine Engineering, İskenderun Technical University, 31200 Hatay, Turkey
[b] Department of Marine Engineering, Yüzüncü Yıl University, 65300 Van, Turkey
[c] Department of Naval Architecture and Marine Engineering, Karadeniz Technical University, 61530 Trabzon, Turkey

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A B S T R A C T

In this study, the cyclic variability of a diesel engine using diesel fuel and butanol–diesel fuel blends is modeled using an artificial neural network (ANN) method. The engine was operated with ten different engine speeds and full load conditions using six different n-butanol–diesel fuel blends. The coefficient of variation (COV) of the indicated mean effective pressure (IMEP), which is a well-accepted evaluation method, was used to assess the cyclic variability for 100 sequential engine cycles. Results indicated that adding n-butanol to diesel fuel caused an increase. Moreover, the COV_{imep} values exhibited a decreasing trend with an increase in the engine speed for each fuel. The experimental results were used to train the ANN. The ANN network was trained with Levenberg – Marquardt (LM) and Scaled Conjugate Gradient (SCG) algorithms. After training the ANN, it was found that the coefficient of determination (R^2) values were in the range of between 0.737 and 0.9677, the mean-absolute-percentage error (MAPE) values were smaller than 8.7 and the mean-square error values (MSE) were smaller than 0.042. The predictions of the developed ANN model showed reasonable consistency with the experimental results.

1. Introduction

Researchers have widely studied new techniques for reducing fuel consumption and producing fewer exhaust emissions, e.g., common-rail injection systems, multiple injection methods, exhaust gas recirculation and after-treatment systems. One of the most promising methods is to use alternative fuels [1]. Due to restricted petroleum supply and rising oil prices, using alternative fuels, such as biodiesel, ethanol, and butanol, has become increasingly important. To comply with the rigorously imposed air pollution standards, the use of renewable energy sources and the development of high-efficiency combustion technologies are required [2].

Compared to biodiesel, the oxygen content in butanol is high; therefore, butanol produces less soot. The use of butanol can play a crucial role in reducing NOx emissions owing to its high heat of vaporization, which decreases its combustion temperature. Therefore, compared with ethanol and biodiesel, butanol has more advantages [3]. In addition, butanol can be blended with diesel fuel without phase separation [4].

Butanol can be produced by the fermentation of biomass (i.e., bio-butanol) such as algae, corn, and various other cellulose-containing crops that cannot be used for food and would otherwise go to waste [1,3,5–7]. Acetone–butanol–ethanol (ABE) fermentation is the oldest known and industrially applied fermentation. ABE fermentation is promoted by bacteria of the genus Clostridium species. This fermentation technique was the only biotechnological method used on an industrial scale until the first half of the twentieth century. A large part of the world's butanol demand (about 66%) were produced by ABE fermentation. The ABE process has been interrupted by the beginning of the production of cheaper butanol by petrochemicals in the 1950s. At the beginning of the 1970s, the oil crisis emerged. Alternative fuels such as biobutanol has become important again. Engineers and companies have focused on biobutanol production. In 2006, BP and DuPont consociated to develop and commercialize biobutanol. In addition, there are many companies working on producing biobutanol such as Butamax, Green Biologics, Gevo, and Cathay Industrial Biotech. Recently, the number of inventions related to the biological production of butanol is increasing. Some patents about

* Corresponding author.
E-mail address: isaltin@ktu.edu.tr (İ. Altın).

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Nomenclature

ANN	Artificial neural network
B3	3%vol. n-butanol + 97%vol. diesel fuel
COV	Coefficients of variation (%)
IMEP	Indicated mean effective pressure (bar)
LM	Levenberg – Marquardt
MAPE	Mean absolute percentage error (–)
MSE	Mean square error (–)
R^2	Coefficient of determination (–)
SCG	Scaled conjugate gradient

fermentation processes for enhanced production of biobutanol have been reviewed in relevant literature [3,8].

Butanol is a four-carbon atom alcohol that exists as 4 isomers: n-butanol (normal-butanol), 2-butanol (secondary-butanol), i-butanol (iso-butanol), and t-butanol (tert-butanol). All isomers have the same formula and the same amount of heat energy; however, their manufacturing methods and molecular structures are completely different, which affect their properties [8]. Because butanol has a low cetane number, which makes autoignition difficult, it cannot be directly used in diesel engines. In general, it is used as an additive to diesel fuel. There are multiple techniques for using butanol as an alternative fuel in diesel engine, such as fumigation [9,10], dual injection systems [11,12], and blends (emulsions) [13,14]. The most practical method is to prepare fuel blends because it does not require any modification on fuel system. Therefore, n-butanol was used as the fuel additive in the present study. There are several important parameters for preferring n-butanol instead of the other isomers. Viscosity of n-butanol is close to viscosity of diesel fuel. The viscosity of the other isomers is high and it negatively affects atomization of fuel. Enthalpy of vaporization of n-butanol is higher than other isomers. N-butanol has high latent heat of evaporation, which absorbs heat from surroundings when it vaporizes. Thus, it cools the cylinder charge and decreases the NOx emissions, which is very important problem for diesel engine. One of the most important parameter for diesel engines is the cetane number of the fuel. Cetane number of n-butanol is close to that of diesel fuel [3].

Combustion cyclic variability is an important parameter associated with the combustion process, which significantly influences fuel consumption and exhaust emissions [15]. There have been numerous studies focusing on cyclic variability in spark-ignition engines; however, there are limited studies focusing on cyclic variability in diesel engines. The combustion of a diesel engine is considered stable; however, addition of an alternative fuel, such as butanol, to diesel fuel affects its combustion stability. Cyclic variations in the combustion process are caused by variations in mixture motion within the cylinder, variations in the amounts of air and fuel fed to the cylinder, and variations in the mixing of fresh mixture and residual gases within the cylinder within each cycle. Another significant factor in cyclic variability is the fuel; the physicochemical properties of the fuel affect combustion and combustion stability [16,17].

The development of a control strategy is becoming increasingly important for higher efficiency combustion and lower emissions. Therefore, an artificial neural network (ANN) was used to model cyclic variability in this study. This model should prove useful in reducing and controlling cyclic combustion variation.

The aim of the study is to investigate the effect of butanol–diesel fuel blends on cyclic variations and develop an ANN model to predict cyclic variability.

Table 1
Specifications of the Hatz 1B40 diesel engine.

Motor type	Air cooled, 4-stroke diesel 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 @ 3600 rpm

2. Materials and methods

2.1. Experimental studies

Experimental studies were conducted on a naturally aspirated, four-stroke, air-cooled, single-cylinder, direct injection Hatz 1B40 diesel engine in Internal Combustion Engines Laboratory, Karadeniz Technical University. The details of the test engine are provided in Table 1, and a schematic of the test system used in the experiments is presented in Fig. 1. A Kistler 6125C piezoelectric pressure sensor was used to measure in-cylinder pressure. It is possible to boost sensitivity to 37 pC/bar and the pressure range to 300 bar. The natural frequency of the piezoelectric transducer is higher than 70 kHz. A Hengstler RI32 incremental encoder was used to measure the crank angle and sense the position of top dead center. The engine was analyzed for 10 engine speeds (1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, and 2800 rpm) and full load conditions. Diesel and 5 different n-butanol–diesel blends were utilized for investigating the effects of n-butanol blending on combustion stability. Blended fuels were prepared as B3 [i.e., n-butanol (3 vol %) + diesel fuel (97 vol %)], B6, B9, B12, and B15. These blends have no additives because phase separation does not occur. The butanol fuel used in this study had a purity of 99.9%. Density, cetane number, kinematic viscosity and flashpoint of fuels were measured in the Prof. Dr. Saadettin GÜNER Fuel Research and Application Center at Karadeniz Technical University. The properties of n-butanol and diesel fuel are summarized in Table 2.

The fuel tank was cleaned before every fuel change and the engine was left to operate for approximately 30 min to reach steady-state conditions before commencing the next test.

2.2. Cyclic variation

Observing the indicator diagram shown in Fig. 2 illustrates that each cycle follows a different path. This is known as cyclic variability or cycle-by-cycle variation.

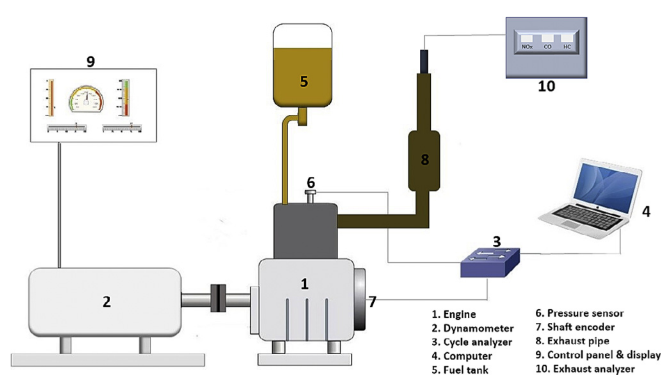

Fig. 1. Schematic of the experimental system.

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