Turboşarjlı Direk Püskürtmeli Bir Dizel Motorunda N-Butanol Fumigasyonunun Motor Performansı ve Eksoz Emisyonları Üzerindeki Etkilerinin Deneysel Olarak İncelenmesi

Zehra Şahin[1], Orhan Nazım Aksu[2], Orhan Durgun[3]

[1]zsahin@ktu.edu.tr; [2]onaksu@ktu.edu.tr; [3]odurgun@ktu.edu.tr

[1] Karadeniz Teknik Üniversitesi, Mühendislik Fakültesi, Makine Mühendisliği Bl., Trabzon
[2] Karadeniz Teknik Üniversitesi, Sürmene Abdullah Kanca Meslek Yüksekokulu
[3]Avrasya Üniversitesi, Makine Mühendisliği Bölümü, Trabzon

Özet

Sunulan çalışmada, n-bütanolun emme havasına püskürtülmesinin (n-bütanol fumigasyonunun, nBF) motor karakteristikleri ve eksoz emisyonları üzerindeki etkileri, Renault K9K 700 tipi turboşarjlı, modern common-rail püskürtme sistemine sahip bir otomobil dizel motorunda deneysel olarak incelenmiştir. Deneyler, çeşitli n-bütanol oranları için (140 Nm, 125 Nm, 110 Nm, 95 Nm ve 80 Nm) gibi beş farklı yükleme durumunda ve 3000 d/d motor hızında gerçekleştirilmiştir. Burada n-bütanol, hacimsel olarak % 2, % 4, % 6, % 8 ve % 10 oranlarında emme havası içerisine basit bir karbüratörle püskürtülmüştür. İlgili karbüratörün ana meme jetini kontrol eden ayar vidası yeniden tasarlanmıştır ve ilgili parça Trabzon piyasasında üretilmiştir. Yapılan deneyler sonunda; seçilen nBF oranları için efektif güç değerlerinin saf dizel yakıtı (SDY) değerleri ile hemen hemen aynı olduğu görülmüştür. Ancak seçilen tüm çalışma koşullarında; özgül yakıt tüketiminin önemli ölçüde arttığı ve efektif verimin ise azaldığı belirlenmiştir. Seçilen nBF oranları için toplam hidro karbonların (THC) ve karbon monoksitin (CO) önemli ölçüde arttığı, ancak azot oksitlerin (NO_x) azaldığı görülmüştür. Duman koyuluğu ise; (140 Nm, 125 Nm ve 110 Nm) gibi yüksek yük değerlerinde artmıştır. Ancak yüksek nBF oranları için artışlar daha yüksek olmuştur. Duman koyuluğu; (95 Nm ve 80 Nm) gibi düşük yük durumlarında ise % 6 nBF oranına kadar azalmıştır, fakat bu orandan sonra ise yeniden artmaya başlamıştır. Sunulan çalışmada, seçilen nBF oranları için toplam yakıt maliyeti SDY'den daha yüksek olmuştur. Bu çalışmanın son bölümünde ise, daha önceden yazarlar tarafından yapılan n-bütanol karışımı deney sonuçları ile nBF deney sonuçları, 3 farklı n-bütanol oranı ve 3 farklı yük durumu için karşılaştırılmıştır.

Anahtar Kelimeler: Dizel motoru, n-butanol fumigasyonu, eksoz emisyonları, motor karakteristikleri, maliyet analizi

Experimental Investigation of the Effects of N-Butanol Fumigation on Engine Performance and Exhaust Emissions in a Turbocharged Diesel Engine

Zehra Şahin[1], Orhan Nazım Aksu[2], Orhan Durgun[3]

[1]zsahin@ktu.edu.tr; [2]onaksu@ktu.edu.tr; [3]odurgun@ktu.edu.tr

[1] Karadeniz Technical University, Engineering Faculty, Mechanical Engineering Dep.,Trabzon
[2] Karadeniz Technical University, Sürmene Abdullah Kanca High School
[3]Avrasya University, Mechanical Engineering Dep., Trabzon

Abstract

In the present study, the effects of n-butanol injection into intake air (n-butanol fumigation, nBF) on the performance and exhaust emissions were experimentally investigated in a Renault K9K 700 type turbocharged common-rail DI automotive diesel engine. Experiments were performed under five different loads such (140 Nm, 125 Nm, 110 Nm, 95 Nm and 80 Nm) and at 3000 rpm engine speed, for various n-butanol ratios. Here, n-butanol was injected into intake air by using an adapted carburetor, which main nozzle section is adjustable to give approximately 2 %, 4 %, 6 %, 8 % and 10 % (by vol.) n-butanol ratios. The test results showed that effective power values for selected nBF ratios are nearly equal to neat diesel fuel (NDF). However, break specific fuel consumption increases and effective efficiency decreases considerably for all of the operating conditions. NO_x emissions decrease, whereas THC and CO increase significantly for all of the selected nBF ratios. Opacity increases for high loads (140 Nm, 125 Nm and 110 Nm) and increment ratios of opacity for high nBF ratios are higher than that of lower nBF ratios. Although opacity decreases under selected low loads (95 Nm and 80 Nm) for low nBF ratios, it starts to increase after 6 % nBF ratio. Also, total fuel cost for selected nBF ratios is higher than NDF. In the present study, the nBF results were also compared with the results of the n-butanol-diesel fuel blends (nBDFBs), which previously investigated experimentally by authors, for three different loads and three n-butanol percentages.

Keywords: Diesel engine, n-butanol fumigation, exhaust emissions, engine characteristics, cost analysis

1. Introduction

Using of diesel automobiles has become widespread for the last 15 years. However, it is explained that the use of diesel automobiles will be banned from 2025 in some countries of Europe. One of the most important reasons for this is environmental pollution. For this reason, a lot of studies have been carried out on the reduction of environmental pollution and also improve engine performance parameters (Goldsworthy, 2013 & Sahin et al., 2015). It is known that alternative fuel studies are among these related studies.

Among the alternative fuels, the most researched fuels are alcohols (Goldsworthy, 2013 & Rakopoulos et al., 2010). But the studies on n-butanol are at limited number compared to the other alcohols in spite of its having more advantages than the other alcohols (Sahin and Aksu, 2015). However, studies for different ratios of n-butanol and diesel fuel blends have been carried out in recent years (Sahin et al., 2015 & Sahin and Aksu, 2015). From these studies, promising results have been obtained in terms of engine performance characteristics and exhaust emissions. As known, alcohols fumigation, especially ethanol fumigation have also been carried out (Goldsworthy, 2013 & Abu-Qudais et al., 2000 & Chen et al., 2013). However, a fewer studies on n-butanol fumigation have been done in literature (Lopez et al., 2015 & Chen et al., 2013). For this reason, in the present study, n-butanol fumigation (nBF) has been investigated experimentally in a modern automotive diesel engine for five different load at 3000 rpm and the obtained results are compared to neat diesel fuel (NDF). Also, in the present study, the nBF results were compared with the results of the n-butanol-diesel fuel blends (nBDFBs), which previously investigated by authors, for three different loads and three different n-butanol percentages.

2. Experimental system and test procedure

2.1. Engine and experimental set up

Experiments for NDF and nBF were conducted in a 4 cylinder, 4-stoke, water-cooled, turbocharged, common-rail injection, 1.461 L Renault DI automotive diesel engine (model K9K 700). Main technical specifications of the engine are given in Table 1 and schematic diagram of the test system used was presented in Fig. 1. The test bed was produced by Cussons. Here; loading was done by a water brake and the brake moment (loading force) was measured electronically. Exhaust emissions were measured by using an exhaust gas analyzer (DiGas 4000, AVL). The accuracies of CO_2 and CO are within ±0.1 % vol and ±0.01 % vol, respectively. Also, the accuracies of HC and NO_x measurement are within 1 ppm.

2.2. Experimental procedure

Here, tests were carried out at 3000 rpm for approximately 2 %, 4 %, 6 %, 8 % and 10 % (by vol.) nBF ratios. Also, five different loads of (140, 125, 110, 95 and 80) Nm were selected. Firstly, NDF tests were conducted as NDF values were required to compare n-butanol addition results. After NDF tests were completed, the adapted carburetor was mounted on the intake manifold of the engine. Fig. 1 presents technical view of the adapted carburetor. Also; to introduce n-butanol into intake air and to measure the amount of the added n-butanol, a small n-butanol tank, a scaled glass bulb and a flexible pipe were used and n-butanol adding unit is shown in Fig. 1. Any other change on the experimental system and engine was not done. The main steps of the experiments are briefly given in the following paragraph.

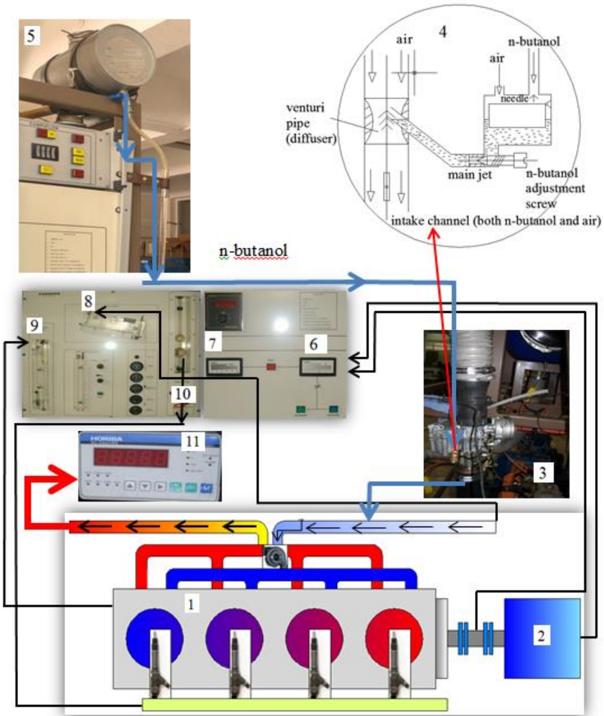

Figure 1. Experimental system. 1-engine, 2-loading unit, 3- adapted carburetor, 4- technical drawing of the adapted carburetor, 5- n-butanol tank, 6-force, 7-speed, 8-air measurement manometer, 9-coolant flow meter, 10-fuel measurement unit, 11- gas analyzer (NO_x analyzer).

The test engine was run for approximately 30 minutes before tests and when temperature of cooling water becomes (70 ±5) °C, that is steady state conditions were reached, experiments for various nBF ratios have been carried out. At 3000 rpm, firstly the engine load was adjusted as 140 Nm. Then, the mean jet opening of carburetor was adjusted to the 1st opening which gives 2 % n-butanol ratio. After approximately 2 % nBF tests were carried out for loading moments between (140-80) Nm; by reducing the engine load at 15 Nm steps and simultaneously adjusting gas throttle levels suitably to obtained constant 3000 rpm. Thus, 2 % nBF tests under five different engine loads were performed. After that, for obtaining 4 % n-butanol ratio, the main jet opening of carburetor was adjusted to the 2nd opening and this opening was again retained fixed at the same 3000 rpm. Thus, tests for % 4 nBF were carried out under (140, 125, 110, 95 and 80) Nm engine loads. Then, similar experimental procedure for approximately (6 %, 8 % and 10 %) nBF ratios were applied.

Table 1. Main technical specifications of the test engine

Engine	Renault K9K 700 turbocharged automotive diesel engine
Displacement	1.461 liter
Number of cylinder	4
Bore & stroke	76 & 80.5 mm
Compression ratio	18.25: 1
Maximum power	48 kW @ 4000 rpm
Maximum torque	160 Nm @ 1750 rpm
Connecting rod length	130 mm

Injection system	Common rail injection system *
Number of nozzle holes	5
Nozzle hole diameter	0.12 mm

*The high pressure ups to 2000 bar

In this study, the effects of nBF on engine performance and exhaust emissions were experimentally studied and compared under different loads and for 3000 rpm engine speed. Here, experiments were conducted for n-butanol ratios (2, 4, 6, 8 and 10 %, by vol.) under five different loads. Tests were firstly carried out for NDF to obtain a database for comparison of the results of nBF. After completed NDF experiments, nBF tests were performed. In the fumigation method, the adapted carburetor was mounted on the inlet manifold of the test engine and thus, n-butanol was introduced into intake air flow. Here; for fumigation tests, to obtain 5 different n-butanol ratios of ~ (2, 4, 6, 8 and 10) %, by vol., carburetor main jet opening was adjusted at 5 different position.

2.3. Calculation of engine performance and determination fumigated fuel properties

In this section, the principles of the calculation of engine performance parameters and determination of fumigated fuel properties for NDF and n-butanol are summarized. The details of the calculation process can be found in references (Durgun, 1990 & Durgun, 2013). In the present study, fuel consumption of the engine was determined by using a scaled glass bulb and consumption duration of 50 mL of diesel fuel was measured. By this way, effective power output, total fuel consumption, brake specific fuel consumption (BSFC) and effective efficiency have been calculated by using the following relations.

$$N_e(kW) = 0.1013\frac{T_b\,\omega}{p_0}\sqrt{T_0/293}\;X_{hum} \tag{1}$$

$$B[kg/h] = \frac{\Delta m_f}{\Delta t} = \frac{\Delta V\,\rho_d\,3600}{\Delta t\;10^6}, \qquad NDF, nBDFBs \tag{2a}$$

$$B[kg/h] = \frac{\Delta m_f}{\Delta t} = \frac{(50\,\rho_d + V_{nB}\,\rho_{nB})\,3600}{\Delta t\;10^6}, \qquad nBF \tag{2b}$$

$$b_e[kg/kWh] = \frac{B}{N_e}, \qquad \eta_e = \frac{3600}{LHV\;b_e} \tag{3a, 3b}$$

In Eq. (1); T_b (Nm) is brake torque, ω is angular velocity of the crankshaft, p_0 (MPa) and T_0 (K) are pressure and temperatures of ambient air, respectively. X_{hum} is the humidity correction factor and it is determined depending on dry and wet thermometer temperatures. In Eqs. (2a) and (3b); ΔV is the volume of consumed diesel fuel, Δt (s) is the duration of consumption of ΔV volume (50 mL) of fuel, ρ_d is the density of diesel fuel, and LHV is the lower heating value of diesel fuel and n-butanol mixture. Here, lower heating values of diesel fuel and n-butanol have been calculated by using well known Mendeleyev formula (Durgun, 2013 & Kolchin and Demidov, 1984).

$$LHV[kJ/kg] = [33.91c' + 125.6h' - 10.89(oy' - s') - 2.51(9h' - w')]\;10^{-3} \tag{4}$$

In Eq. (4), c', h', oy', s' and w' represent elemental composition of fuel, and their values for diesel fuel and n-butanol have been given in Table 2. For fumigation case, lower heating values have been determined by using the following relation given by Durgun 1990 & 2013.

$$LHV_{nBF}[kJ/kg] = \frac{\sum_{i=1}^{n}(x_i\ \rho_i\ LHV_i)}{\sum_{i=1}^{n}(x_i\ \rho_i)} = \frac{x_d\ \rho_d\ LHV_d + x_{nB}\ \rho_{nB}\ LHV_{nB}}{x_d\ \rho_d + x_{nB}\ \rho_{nB}} \tag{5}$$

where ρ_d and ρ_{nB} are the densities of diesel fuel and n-butanol respectively, and x_d and x_{nB} are the volumetric percentages of diesel fuel and n-butanol in the mixture, respectively. In the present study, to see clearly the effects of nBF addition on engine performance and exhaust emissions, variation ratios of engine performance characteristics and exhaust emissions in respect of NDF were calculated. For example, variation ratio of BSFC was computed as follows:

$$\frac{\Delta b_e}{b_e}\times 100[\%] = \left[\left(b_{e,nBF} - b_{e,d}\right)/b_{e,d}\right]100 \tag{6}$$

where $b_{e,nBF}$ and $b_{e,d}$ are bsfc values for fumigated fuel and diesel fuel, respectively.

2.4. Cost analysis

In the present study, cost analysis has also been done by using the practical relationship, which was proposed originally by Durgun (2013). Here, by using variation ratio of BSFC in respect to NDF and the actual prices of n-butanol and diesel fuel, combined fuel cost variation for fumigated fuel is calculated and compared. For this purpose, the following formula has been used.

$$\frac{\Delta C}{C_1}\times 100[\%] = \frac{C_2 - C_1}{C_1}\ 100 = \left[\frac{x_1 + \sum_2^n X_i\ r_i}{x_1 + \sum_2^n X_i\ s_i}\left(1 + \frac{\Delta b_e}{b_e}\right) - 1\right]100 \tag{7}$$

where

$$r_i = C_i/C_1, \quad r_1 = C_1/C_1 = 1, \quad r_2 = C_2/C_1 = 84/4.62 = 18.18182$$

$$s_i = \rho_i/\rho_d, \quad s_1 = \rho_d/\rho_d = 1, \quad s_2 = \rho_{nB}/\rho_d = 794/823 = 0.9647$$

C_1 is cost of diesel fuel, C_2 is cost of n-butanol and $\Delta b_e/b_e$ is difference ratio of BSFC, ρ_{nB} and ρ_d are densities of n-butanol and diesel fuel, respectively. Here, units of (C_1, C_2), (ρ_{nB}, ρ_d) and b_e are (TL/lt), (kg/m^3) and (kg/kWh) respectively. In Trabzon, Turkey for 2017 currency, ***1$ is equal to 3.53 TL.*** The costs and other main characteristics of diesel fuel and n-butanol (and also ethanol) are given in Table 2.

Tablo 2. The main properties of diesel fuel, ethanol and n-butanol (Sahin et al., 2015 & Dogan, 2011 & Sahin and Aksu, 2015 & Chen et al., 2013)

	Diesel fuel	**Ethanol**	**n-Butanol**
Chemical formula	$C_{14.342}H_{24.75}$	C_2H_5OH	C_4H_9OH
Moleculer mass [kg/kmol]	197.21**	46.07**	74.123**
Density [kg/m^3]	823 *	785	794*
Lower heating value [kJ/kg]	42685.7**	27423.24**	33630.8**

Cetane number	45	8	25
Latent heat of evaporation [kJ/kg]	270	904	581.4
Boiling point [^{0}C]	180-360	78	118
Flash point [^{0}C]	≥55	13-14	35-37
Kinematic viskosity, at 20 ^{0}C, [mm^2/s]	3.4	1.20	3.64
Composition, mass [%]	$c' = 0.873$, $h' = 0.127$	$c' = 0.521$, $h' = 0.131$, $oy' = 0.347$	$c' = 0.648$, $h' = 0.136$, $oy' = 0.216$
Cost [TL/lt], July 2017 , 1$=3.53 TL***	4.62	16 (99,8 % purity)	84 (99,9 % purity)

*measured in laboratory, **calculated from Mendeleyev formula, *** TL: Turkish Lira

2.5. Error analysis and uncertainties

Error analysis was applied to the measured values and uncertainties were also determined by using Kline and Mc.Clintock's method (Holman, 2001). Here, each value has been measured 3 times and for this reason Student's t-distribution has been applied to the experimental data. By the evaluation of measured data, uncertainty intervals of torque, effective power and BSFC values were determined at the levels of (0.1-0.5) %, (0.04-0.5) % and (0.1-6.5) %, respectively. From these results, it can be stated that the probably uncertainties in the measuring of the principle values and in the derived values would not affect significantly the uncertainties of the numerical results.

3. Results and discussions

In this paragraph tests results, related to the influences of the nBF on engine performance and exhaust emissions have been given and compared to NDF in various figures. By inspecting of these figures and evaluating obtained experimental data and calculated parameters, various discussions have been done. Moreover, in the present study, the nBF results were compared with the results of the n-butanol-diesel fuel blends (nBDFBs), which previously investigated by authors, for three different loads and three different n-butanol percentages (Aksu, 2013). The comparison results are presented in the following paragraph in the form of bar graphs.

3.1. The effects of n-butanol fumigation on engine performance and exhaust emissions

Fig. 2a and Fig. 2b show the variations and variation ratios of effective power versus to the nBF for five different engine loads, respectively. As can be seen in Figs.2 (a and b), effective power values for selected nBF ratios are nearly equal to NDF values. However, it starts to decrease after 8 % nBF ratio. Figs. 3 (a and b) Figs. 4 (a and b) show the variations and variation ratios of BSFC and effective efficiency versus to the nBF ratios for five different engine loads, respectively. It can be observed that for all the nBF ratios, BSFC increases significantly. The occurred maximum increase ratio of BSFC is 13.59 % for 10 % nBF ratio, under 140 Nm load. Similar results have also been reported by earlier researcher (Dogan, 2011 & Rakopoulos, 2010 & Lopez et al., 2015). It is well known that the flame temperature of n-butanol is smaller than that of diesel fuel (Dogan, 2011 & Lopez et al., 2015). Thus, as expected, the combustion temperature values may reduce with increasing of the amount of n-butanol in the combustion chamber. Low cylinder temperatures may produce incomplete combustion and higher BSFC. Also, lower heating value of n-butanol is lower than that of diesel fuel. This could also increase BSFC. Furthermore, as can be seen in Figs. 5, excess air coefficient decreases with increasing nBF ratios (Lopez et al., 2015). This may be attributed to the engine running under overall 'richer', which may produce incomplete combustion and higher BSFC and exhaust emissions. It can be clearly seen from Eq. (3b) that effective efficiency is simply the inverse of the product of BSFC and as expected effective efficiency decreases for selected n-butanol ratios.

In the present study, carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbon (THC), and nitrogen oxides (NO_x) were measured for various nBF ratios, under five loads. Figs.6 (a and b) present variations and variation ratios of CO_2 for five different nBF ratios, respectively. It can be seen from these figures that CO_2 percentage generally increases for selected nBF ratios. It can be conducted that the combustion process is not improved by applying nBF in contrast to expectations. As a result, CO has also increased as can be shown in Figs 7. The same results have been obtained by Andrés et al and they explained that the causes of the increase in CO are incomplete combustion and partial fuel oxidation due to low cylinder temperature in combustion chamber. Also, insufficient evaporation of n-butanol liquid droplets adhering to oil layer in the chamber walls might increase CO and THC (Lopez et al., 2015). It is estimated that the same phenomena for n-butanol fumigation might be occur in the present study. As can be seen in Figs.8 (a and b) that NO_x emissions increase up to 6 % n-butanol ratio, but after this ratio they start to decrease. It is thought that n-butanol addition decreases the cylinder temperature and also excess air coefficient values. These phenomena could decrease in NO_x emissions (Dogan, 2011 & Lopez et al., 2015) especially at high n-butanol ratios. The obtained maximum decrease ratio of NO_x emission is 10.91 % for 10 % nBF ratio and 125 Nm.

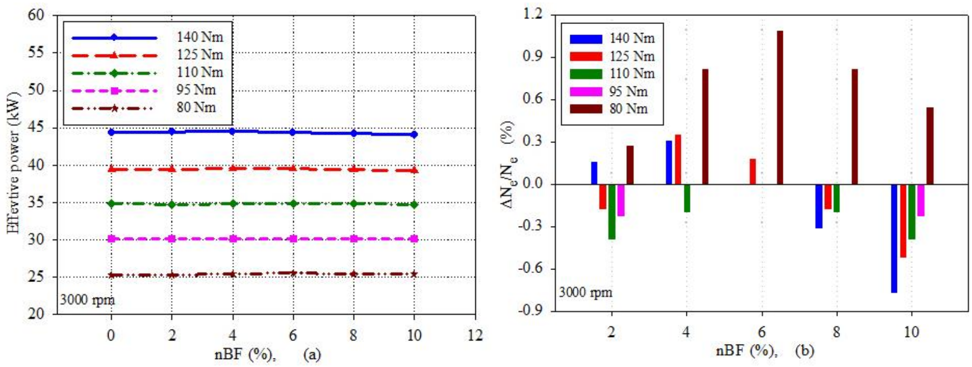

Figure 2 (a and b). Variations and variation ratios of effective power versus different n-butanol ratios under five different loads, respectively.

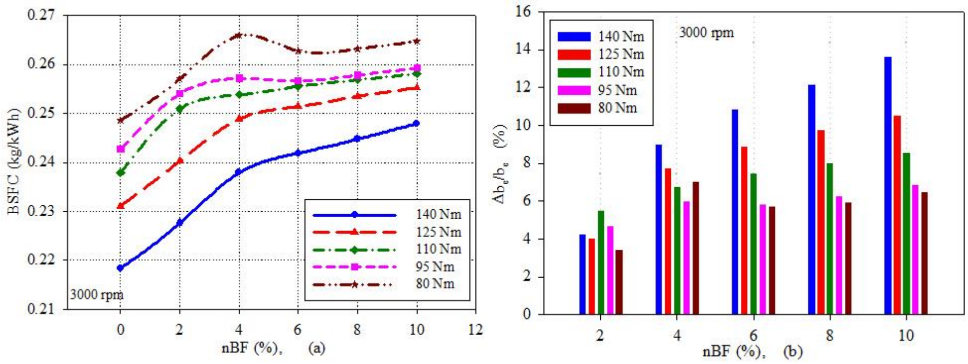

Figure 3 (a and b). Variations and variation ratios of BSFC versus different n-butanol ratios under five different loads, respectively.

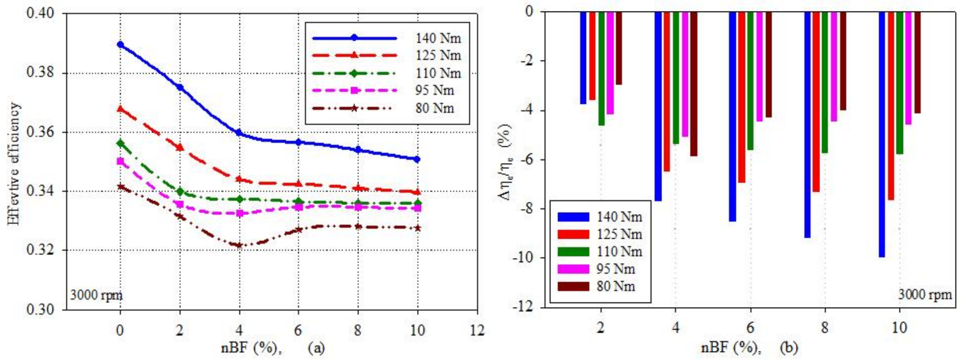

Figure 4 (a and b). Variations and variation ratios of effective efficiency versus different n-butanol ratios under five different loads, respectively.

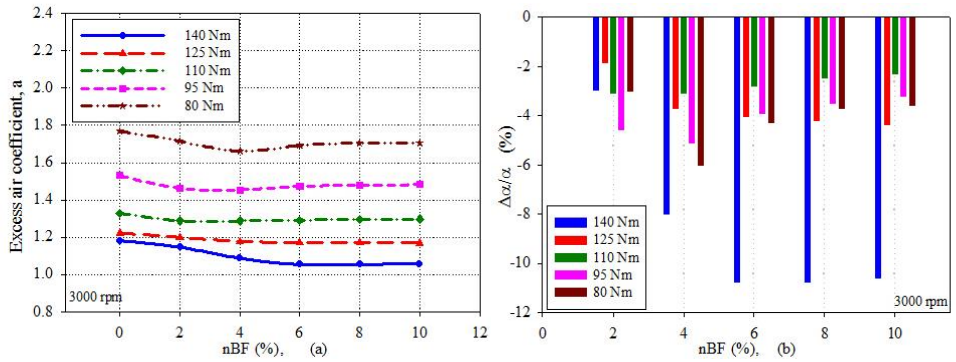

Figure 5 (a and b). Variations and variation ratios of excess air coefficient versus different n-butanol ratios under five different loads, respectively.

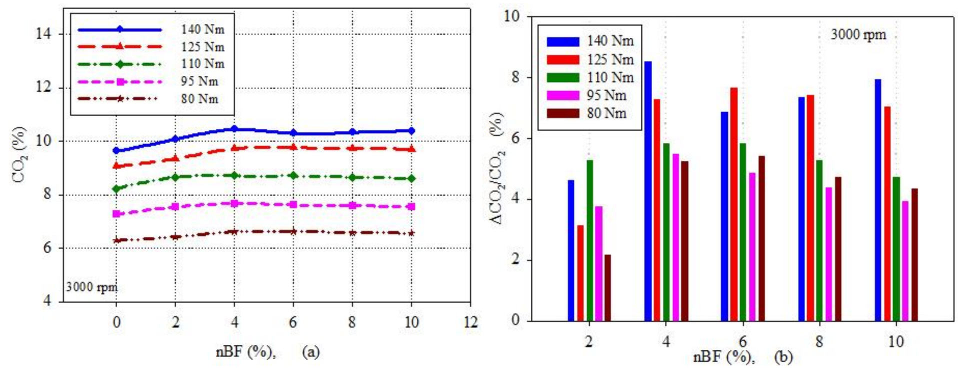

Figure 6 (a and b). Variations and variation ratios of CO_2 versus different n-butanol ratios under five different loads, respectively.

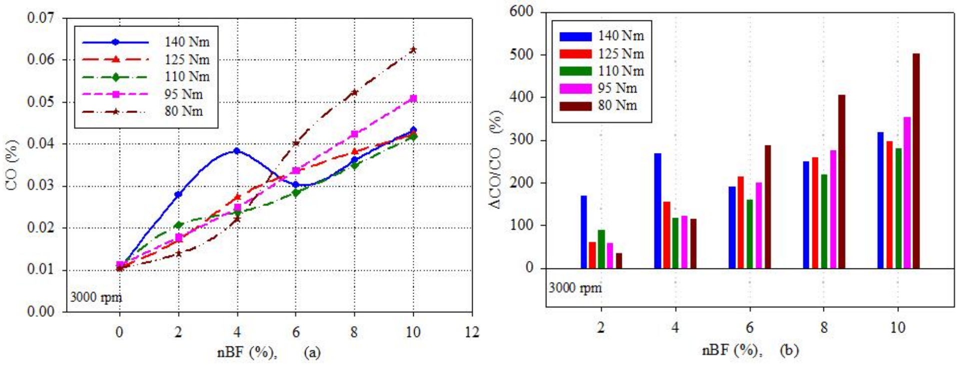

Figure 7 (a and b). Variations and variation ratios of CO versus different n-butanol ratios under five different loads, respectively.

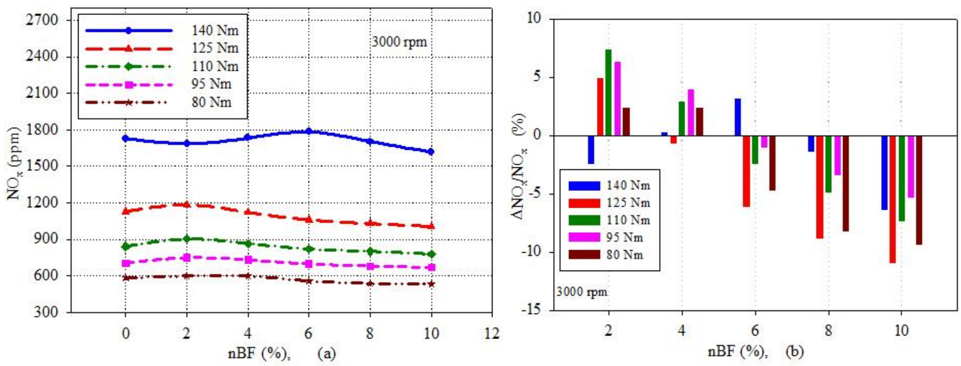

Figure 8 (a and b). Variations and variation ratios of NO_x versus different n-butanol ratios under five different loads, respectively.

As can be seen in Figs. 9 that THC emissions increase importantly with nBF. The increment ratios of THC for lower loads are higher than that of higher loads. As it is mentioned earlier, the flame temperature of n-butanol is lower than that of diesel fuel (Dogan, 2011 & Lopez et al., 2015). This may result in lower cylinder temperature and pressure values. Thus, the reduced temperature values cause higher THC emissions levers. Similar trends were reported in Refs. (Dogan, 2011 & Rakopoulos, 2010). Figs.10 (a and b) present variations and variation ratios of opacity for different nBF ratios, respectively. In contrast to expectations, the value of the opacity has been increased by applying nBF. The increment ratios of opacity for lower n-butanol ratios are lower than that of higher n-butanol percentages. Goldsworthy (2013) also reported that opacity increases at high ethanol fumigation rates. He explained that at higher ethanol rates, the premixed combustion of the ethanol may be reducing the oxygen immediately available to the injected fuel which would lead to reduced soot burnout and thus increased exhaust opacity (Goldsworthy, 2013). *It is thought that a similar phenomenon might be occur by applying n-butanol fumigation.*

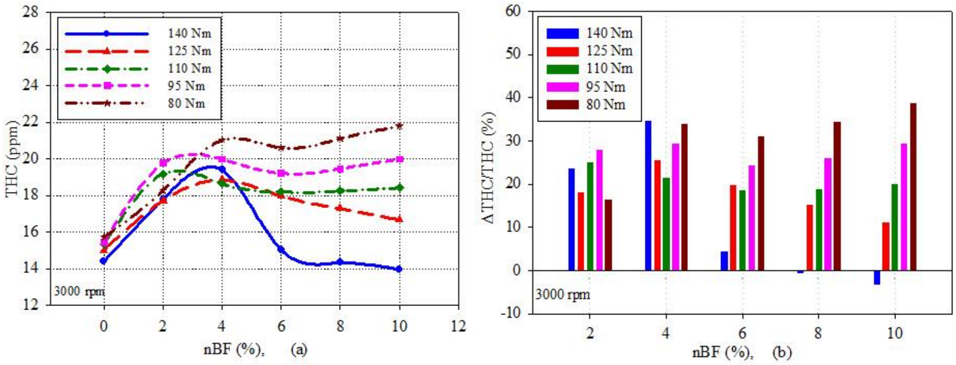

Figure 9 (a and b). Variations and variation ratios of THC versus different n-butanol ratios under five different loads, respectively.

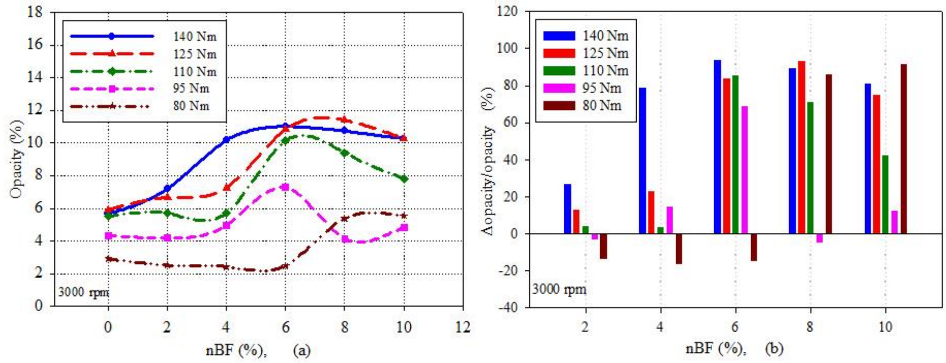

Figure 10 (a and b). Variations and variation ratios of opacity versus different n-butanol ratios under five different loads, respectively.

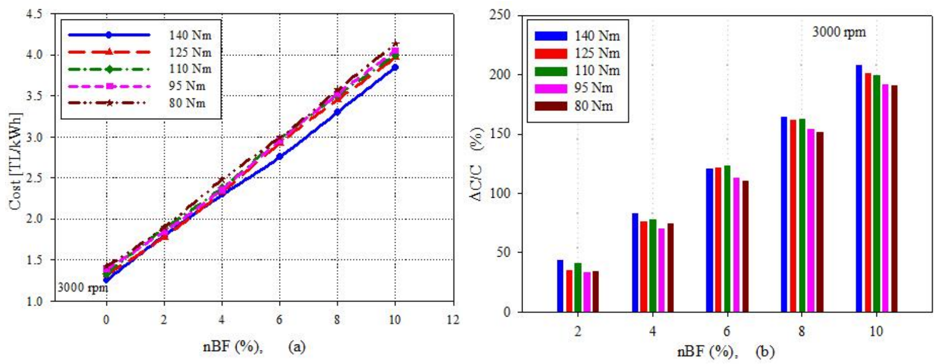

Figure 11 (a and b). Variations and variation ratios of cost versus different n-butanol ratios under five different loads, respectively.

Variations and variation ratios of the fuel cost compared to NDF for different loads were presented in the Figs. 11(a-b), respectively. As can be seen from these figures that the total cost of fuel takes higher values than that of NDF at all of the operating conditions. Because the price of n-butanol is eighteen times of diesel fuel in Turkey, the total fuel cost becomes higher than that of diesel fuel.

3.2. Comparison of n-butanol fumigation and n-butanol-diesel fuel blends

The effect of nBF and nBDFB on the effective power is shown in Fig. 12. As can be seen in this figure, effective power decreases significantly for nBDFBs. Due to lower heating value of n-butanol, energy content of the nBDFBs is lower than that of diesel fuel. Thus, effective power of nBDFBs take lower values than that of NDF. However, the values of effective power for nBF are nearly equal to NDF values. In the fumigation method, the amount of diesel fuel has not been changed and additionally n-butanol has been introduced to intake air in the intake channel. As n-butanol is added in addition to diesel fuel, effective power has not changed significantly (Aksu, 2013).

The variation ratios of BSFC versus n-butanol ratios for blending and fumigation methods are presented in Fig.13. As can be seen in this figure that, BSFC slightly decreases for 2 % and 4 % nBDFBs, but it slightly increases for 6 % nBDFB at selected engine loads. As lower heating value of n-butanol is smaller than that of diesel fuel, naturally BSFC takes higher values as n-butanol percentages increases. That is, the engine consumes more fuel to produce the same effective power and consequently BSFC increases. Fig. 14 shows the variation ratios of effective efficiency versus n-butanol ratios for blending and fumigation methods. As can be seen in this figure, brake effective efficiency increases for nBDFBs. On the other hand, increment ratios of effective efficiency decreases for high n-butanol percentages (Dogan, 2011 & Aksu, 2013 & Yao et al., 2010).

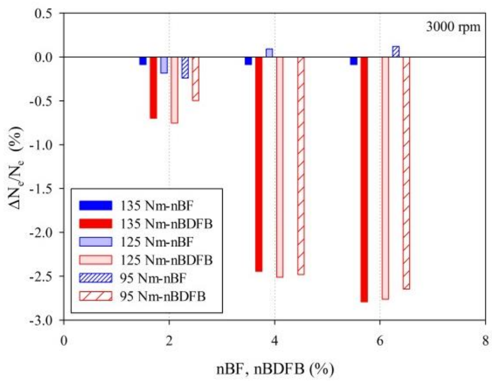

Figure 12. Variations ratios of effective power versus different n-butanol ratios for three different loads at 3000 rpm.

For nBF, BSFC increases significantly for selected loads and n-butanol percentages. As can be seen in Eq. (2b) that, in the fumigation method the amount of diesel fuel has not been changed and n-butanol has been introduced to intake air in the intake channel as additional fuel. As n-butanol is added diesel fuel, BSFC naturally decreases. As explained above paragraph, the combustion temperature values may reduce with increasing of the amount of n-butanol in the combustion chamber. Low cylinder temperatures may produce incomplete combustion and higher BSFC. Contrary to expectations, the improvement effect of n-butanol fumigation on combustion process was determined to be small. As can be seen in Fig. 14, brake thermal efficiency decreases obviously for nBF.

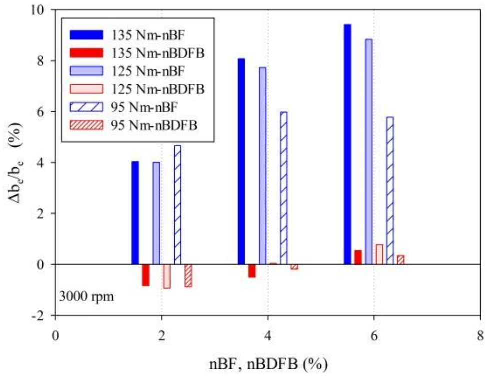

Figure 13. Variations ratios of BSFC versus different n-butanol ratios for three different loads at 3000 rpm.

The variations ratios of NO_x emission for various n-butanol blends and fumigation for three different loads are given in Figs. 15. As can be observed in these figures that; for n-butanol blends, NO_x emission decreases for 2 % and 4 % nBDFBs, but it increases for 6 % nBDFB under 135 Nm and 125 Nm loads. NO_x emission increases for selected n-butanol percentages under 95 Nm load. n-butanol blends generally produces lower flame temperature due to its lower energy content and higher heat of evaporation. This results in lower combustion temperature. The lower temperatures naturally decrease NO_x emissions (Chen et al., 2013 & Aksu, 2013 & Yao et al., 2010).

For nBF, NO_x emission increases until 4 % n-butanol percentages but after this ratio it effectively decreases. It is thought that n-butanol addition by fumigation method decreases the cylinder temperature and also excess air coefficient values. These phenomena could decrease NO_x emissions (Dogan, 2011 & Lopez et al., 2015) especially at higher n-butanol ratios.

Variations ratios of total fuel cost for the nBDFBs and nBF compared to NDF for different loads at 3000 rpm were presented in the Figs. 16. As can be seen from this figure that the total cost of fuel takes higher values than that of NDF for nBDFBs and nBF. Total fuel cost becomes higher than that of diesel fuel, because the price of n-butanol is approximately eighteen times of diesel fuel in Turkey. Also, combined cost of fuel for nBF is higher than that of nBDFBs because of rising BSFC for fumigation method.

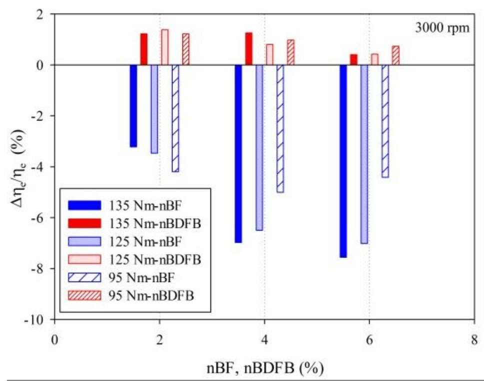

Figure 14. Variations ratios of effective efficiency versus different n-butanol ratios for three different loads at 3000 rpm.

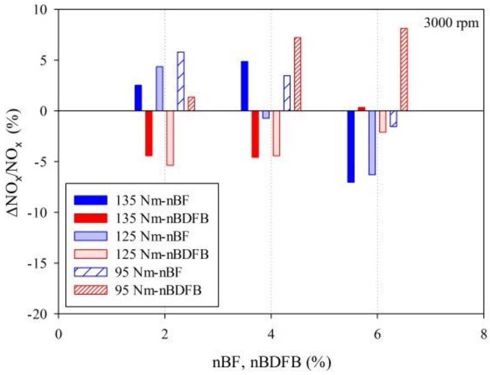

Figure 15. Variations ratios of NO_x emissions versus different n-butanol ratios for three different loads at 3000 rpm.

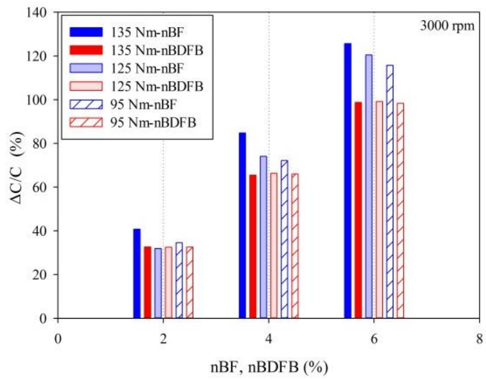

Figure 16. Variations ratios of cost versus different n-butanol ratios for three different loads at 3000 rpm.

4. Conclusions

In the present study the effects of n-butanol addition into intake air on engine performance, emission characteristics and fuel cost were investigated experimentally and compared with that of NDF in an automotive DI diesel. Also, the nBF results were compared with the results of the n-butanol-diesel fuel blends (nBDFBs), which previously investigated experimentally in the same engine by authors, for three different loads and n-butanol percentages. Based on the experimental results the main effects of the n-butanol addition can be summarized as follows:

1. n-Butanol addition into the intake manifold increases the BSFC and decreases effective efficiency under selected five different loads at 3000 rpm. The observed maximum increase ratio of BSFC is 13.59 % for 10 % nBF ratio under 140 Nm. However, effective power values for selected nBF ratios are nearly equal to neat diesel fuel values.

2. n-Butanol addition into the intake manifold increases CO_2, CO and THC for selected loads. The determined maximum increase ratio of THC is 38.73 % for 10 % nBF ratio under 80 Nm load. Opacity generally increases for nBF. However, it decreases slightly for low n-butanol ratios and low loads. NO_x emissions increase until 6 % n-butanol ratio, but after this ratio they start to decrease. The obtained maximum decrease ratio of NO_x emission is 10.91 % for 10 % nBF ratio and 125 Nm.

3. n-Butanol addition has not given good results in terms of engine performance characteristics and exhaust emissions for selected loads at 3000 rpm. Only NO_x emissions have started to decrease after 6 % n-butanol ratios.

Here, for nBF, no changes were made to the engine operating conditions. However, it is expected that if the injection system, especially injection advance end injection pressure, were optimized for nBF, more hopeful results for engine performance characteristics and exhaust emissions may be attained.

4. n-Butanol-diesel fuel blends decrease effective power and BSFC. NO_x emissions decreases slightly until 4 % n-butanol percentage, but after this ratio it starts to increases for this method. However, effective power for the fumigation method has not changed much. But, BSFC increases obviously in this method. The total cost of fuel takes higher values than that of NDF for nBDFBs and nBF. Also, combined cost of fuel for nBF is higher than that of nBDFBs because of being increase of BSFC for fumigation method. Low n-butanol-diesel fuel blends have given good results in terms of engine performance parameters. But n-butanol fumigation has not produced good results for engine performance parameters.

NO_x emissions reduce for low nBDFB ratios such as 2 % and 4 %, while NO_x emissions increase for these ratios for the fumigation method. But for 6 % n-butanol percentages, NO_x emissions decrease significantly for the fumigation method but they increase for the blending method. Low nBDFBs such as 2 % and 4 % have given good results in terms NO_x emissions. However; in the fumigation method, 6 % n-butanol percentage and higher percentages gave positive effects in respect of the reduction of NO_x emissions.

Acknowledgement

We would like to present our thanks to Karadeniz Technical University Scientific Research Unit for the financial support through the project FAY-2015-5195 and Mechanical Engineering Dep. Internal Comb. Engine Lab. Technician Şenol DÜBÜŞ who has assisted to the experiments.

References

Abu-Qudais, M., Haddad, O. & Qudaisat, M. (2000). “The effect of alcohol fumigation on diesel engine performance and emissions,” *Energy Conversion and Man.*, vol. 41, no. 4, pp. 389-399.

Aksu, O. N. (2013) “Experimental Investigation of the Effects of the Use of n-Butanol-Diesel Fuel Blends on Engine Characteristics and Exhaust Emissions in a Turbocharged Diesel Engine”, *Master Thesis, K.T.U., Institute of Science and Technology*, Trabzon.

Chen, Z., Liu, J., Wu, Z. & Lee, C. (2013). “Effects of port fuel injection (PFI) of n-butanol and EGR on combustion and emissions of a direct injection diesel engine,” *Energy Conversion and Management*, vol. 76, pp. 725-731.

Dogan, O. (2011). “The Influence of n-butanol/diesel fuel blends utilization on a small diesel performance and emissions,” *Fuel*, vol. 90, no. 7, pp. 2467-2472.

Durgun, O. (1990). “Experimental Methods in Engines, Lecturer notes for laboratory,” *Karadeniz Technical University, Engineering Faculty, Mechanical Engineering Department.*

Durgun, O. (2013). “Fuels and Combustion, Lecturer notes,” *Karadeniz Technical University, Engineering Faculty, Mechanical Engineering Department.*

Goldsworthy, L. (2013). “Fumigation of a heavy duty common rail marine diesel engine with ethanol–water mixtures,” *Experimental Thermal and Fluid Science,* vol. 47, pp. 48-59.

Holman, J. P. (2001). “Experimental Methods for Engineers,” McGraw Hill Press, New-York.

Kolchin, A., & Demidov, V. (1984). “Design of Automotive Engines,” Mir Publishers, Moscow.

López, A. F., Cadrazco, V., Agudelo, A. F., Corredor, L. A., Vélez, J. A. & Agudelo, J. R. (2015). “Impact of n-butanol and hydrous ethanol fumigation on the performance and pollutant emissions of an automotive diesel engine,” *Fuel*, vol. 153, pp. 483-491.

Rakopoulos, D. C., Rakopoulos, C. D., Giakoumis, E. G., Dimaratos, A. M., Kyritsis, D. C. (2010). “Effects of butanol-diesel fuel blends on the performance and emissions of a high-speed DI diesel engine,” *Energy Conversion and Management,* vol. 51, no. 10, pp. 1989-1997.

Sahin, Z., Durgun, O. & Kurt, M. (2015). “Experimental investigation of improving diesel combustion and engine performance by ethanol fumigation-heat release and flammability analysis,” *Energy Conversion and Management,* vol. 89, pp. 175-187.

Sahin, Z. & Aksu, O. N. (2015). “Experimental investigation of the effects of using low ratio n-butanol/diesel fuel blends on engine performance and exhaust emissions in a turbocharged DI diesel engine,” *Renewable Energy,* vol. 77, pp. 279-290.

Siwale, L., Kristof, L., Adam, T., Bereczky, A., Mbarawa, M., Penninger, A. & Kolesnikov, A. (2013). “Combustion and emission characteristics of n-butanol/diesel fuel blend in a turbo-charged compression ignition engine,” *Fuel*, vol. 107, pp. 409-418.

Tutak W. (2014). “Bioethanol E85 as a fuel for dual fuel diesel engine,” *Energy Conversion and Management,* vol. 86, pp. 39-48.

Yao, M., Wang, H., Zheng, Z. & Yue, Y. (2010). “Experimental Study of N-Butanol Additive and Multi-Injection on HD Diesel Engine Performance and Emissions”, *Fuel*, vol. 89, pp. 2191-2201.