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Numerical Investigation of n-Butanol Addition on the Performance and Emission Characteristics of CI Diesel Engine

Salman Abdu Ahmed*, [1], Song Zhou*, Yuanqing Zhu*, and Yongming Feng*

Abstract – *The demand for higher output efficiencies, greater specific power output, increased reliability, and ever reduced emissions has been rising. Due to its availability one promising alternative is the use of butanol in internal combustion engines. In this study, the effects of n-butanol addition (5%, 15% and 25% by volume) to diesel fuel on the performance and exhaust emissions of a 6 cylinder four stroke turbocharged direct injection CI Diesel engine were investigated using GT-Power computational simulation tool. The simulations were performed by varying the engine speed between 1000 and 2000 rpm at four different loads of brake mean effective pressure (bmep) (4.5, 8.5, 10.5 and 12.75 bar). The performance and exhaust emissions of the engine when working with the three butanol-diesel blends were compared with neat diesel fuel. The results showed that the butanol-diesel blends reduced carbon monoxide (CO) and nitrogen oxide (NO_X) by about 40% and 70% respectively, However carbon dioxide (CO_2) and unburned hydrocarbon (HC) emissions increased. It was also found that the brake thermal efficiency (BTE) improved by more than 20% for butanol diesel blends when compared with the corresponding diesel fuel. Due to its optimum values in terms of emission and performance parameters 15% butanol-diesel blend was found to be the best choice.*

Keywords – biofuels, butanol-diesel blend, diesel engine, emission, engine performance.

1. INTRODUCTION

Due to fast depletion of fossil fuels, environmental concerns, and strict governmental regulations on exhaust emissions led engine manufacturers to conduct research on viable alternative fuels for meeting sustainable energy demand. Diesel engines are the most efficient combustion engine today and they play an important role in transport of goods and passengers on road and on high seas. They are attractive due to their high power output, good fuel conversion efficiency, relatively low fuel consumption and high durability [1], [2]. Even though diesel engines are well known for their higher efficiency and fuel economy their combustion results in the emission of noxious pollutants which have an adverse effect both on the environment and human health [3]. The main pollutants consist of nitric oxide and nitrogen dioxide (NOx), carbon monoxide, unburned hydrocarbons, smoke and particulate matter.

In order to control and minimize emissions the International Maritime Organization (IMO) and other regulatory bodies introduced legislation for limiting non-greenhouse gaseous emissions including NOx and SO_X, as well as the greenhouse gaseous emissions [4]. In compliance with the strict regulations to control emission a lot of research has been conducted to improve the combustion characteristics, so that to maximize the engine efficiency, thus reducing fuel consumption, and harmful gaseous emissions. Significant achievements for the development of cleaner diesel engines have been made by following various engine-related techniques, such as for example the use of common-rail systems, fuel injection control strategies, exhaust gas recirculation, exhaust gas after-treatment *etc*. [5], [6]. For the reduction of emitted pollutants, researchers have focused their interest on the domain of fuel related techniques such as, for example, the use of alternative fuels, often in fumigated form, or gaseous fuels of renewable nature that are environmentally friendly.

One promising alternative is the use of alternative fuel for diesel engines. Alcohol fuels such as methanol (CH_3OH), ethanol (C_2H_5OH), and butanol (C_4H_9OH) can be used with diesel fuels in various percentage blends for CI engine as a clean alternative fuel source [7]. Butanol is a feasible alternative fuel or fuel additive for use in CI engines and provides number of desirable properties compared to ethanol and methanol such as, higher cetane number, lower heat of vaporization, higher heating value, no corrosion to pipelines, and better miscibility and inter solubility with diesel fuel [8]. Moreover, butanol has higher energy density than ethanol and methanol [9] and can be blended with diesel fuel without phase separation [10]. It is produce by fermentation of biomass, algae, corn and plant materials that contain cellulose [10]. There are three approaches in using butanol in diesel engines. These approaches are butanol–diesel fuel blend [11], [12] (mixture of the fuels prior to injection), butanol fumigation [13], [14] (addition of alcohols to the intake air charge.) and dual injection system [11] (separate injection systems for each fuel).

Several researchers have conducted experimental investigation on the diesel engine fueled with diesel blended fuels. Many studies explain that the use of diesel blended fuels related to improving performance and lowering exhaust emissions. Yusri *et al.* [15] conducted a test using 10% n-butanol blend to investigate the combustion and emissions of a multi-cylinder, 4-stroke engine with common rail direct

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injection system. In that study the test results showed 73.4% decrease in NO_X emissions at a speed of 2500rm when compared with neat diesel operation. Rakopoulos *et al.* [16], [17] performed experimental tests on a single-cylinder, compression–ignition, direct injection and naturally aspirated diesel engine. They showed that the addition of n-butanol (8%, 16% and 24%, by vol.) to diesel fuel increased the brake specific fuel consumption (BSFC), BTE and unburned HC emissions while significantly decreased CO, NOx and soot. Jian Wu *et al.* [18] performed a simulation using AVL FIRE ESE Diesel and studied the combustion and emission characteristics of diesel engine using pure diesel and different proportions of n-butanol/diesel fuel mixture. The simulation results showed a decrease in CO and soot emission however, BSFC increased. Doğan *et al.* [10] conducted a test in a small diesel engine to study the influence of n-butanol-diesel fuel blends (as an oxygenation additive for the diesel fuel) on engine performance and exhaust emissions. The experimental test results showed that smoke opacity, nitrogen oxides, and carbon monoxide emissions reduced while hydrocarbon emissions increased with the increasing n-butanol content in the fuel blends.

In another study Yao *et al.* [19] investigated the effects of butanol ratios (5%, 10% and 15%) by volume in diesel blends on a six cylinder diesel engine equipped with common rail injection system. The results showed that increasing butanol in the blends led to reduction of CO and soot emissions with little increase in BSFC. Siwale *et al.*[20] experimentally investigated the effects of n-butanol addition (5%, 10% and 15% by volume) to diesel on the performance and emissions of a four-cylinder piston, 1.91L - 66 kW Turbo-Direct Injection (TDI) Volkswagen diesel engine. In that study the experimental results showed that the n-butanol addition decreased BSFC and exhaust gas temperature while BTE increased. Akar [21] conducted experiment and studied the fuel properties, engine performance, and emission characteristics of diesel fuel, false flax biodiesel, and their blends with butanol. In that study the investigations showed an increase in Specific fuel consumption with the increase of butanol addition. There was a slight increase of NO_X and reduced CO and CO_2 emissions.

Rakopoulos *et al.* [16], [17], [22], Huang *et al.* [23], Zhang *et al.* [24], Altun *et al.* [25], and de Chen [26] are some of the researchers who conducted experimental studies on the effects of butanol diesel fuel blends. Leermakers *et al.* [27] studied butanol-diesel blends with respect to emissions and efficiency in a partially premixed combustion .They observed lower CO and HC emissions. Merola *et al.* [28] investigated the effects of butanol diesel blends through conventional methods and optical diagnostics in a four cylinders, turbocharged, water cooled, and DI diesel engine. They found smokeless conditions with a slight increase in NOx emissions. Swamy *et al.*[29] carried out experimental investigation to study and asses combustion, performance and emission characteristics of diesel engine using four different blends of n-Butanol (5%,10%,15% and 25% by volume). The results showed increased HC, slightly higher NO_X and reduced CO emissions.

A simulation was conducted to investigate the performance and exhaust emissions of blends of n-butanol with conventional diesel fuel with 5%,15% and 25% (by vol.) n-butanol in a six cylinder ,turbocharged and direct injection diesel engine. The simulation was conducted without any modification to the conventional diesel engine. The purpose of the present work was to investigate the effects of n-butanol addition to diesel fuel on engine performance and exhaust emissions at different operating conditions. The simulation results were analyzed and compared with the base diesel engine running at the same operating conditions.

2. ENGINE MODELLING

The engine developed in the present work is a six cylinders, direct injection, turbocharged and in-line engine. As explained in the introduction part there are various techniques involving butanol–diesel dual fuel operation. In this study, the butanol–diesel fuel blend technique was used to investigate the effects of butanol addition on the performance and emissions of the given engine. The main parameters of the engine are given in Table 1.

Table 1. Engine parameters.

Engine parameters	Values
Maximum continuous rating (MCR)	298 [kW]
Bore	119 [mm]
Stroke	175 [mm]
Connecting rod length	300 [mm]
Total displacement	11.7 [L]
Cylinder configuration	6 in-line
Compression ratio	16.5
Turbocharger	1 unit
Fuel injection nozzle	8 holes
Injection pressure	500 [bar]

The software used in the present work is GT-Power, which is widely used 1D simulation program for engine modelling and analysis .It is designed applicable to all types of internal combustion engines. The engine mentioned above was modelled by using different blocks and interconnections that represent the engine layout. The following input data are need to set up the model: the engine geometric data ,the intake and exhaust valve profiles ,the compressor and turbine performance maps, the constants of engine sub model (combustion, heat transfer and friction), the engine operating point (load/speed) and the ambient conditions. The developed GT-POWER model of the engine is shown in Figure 1.

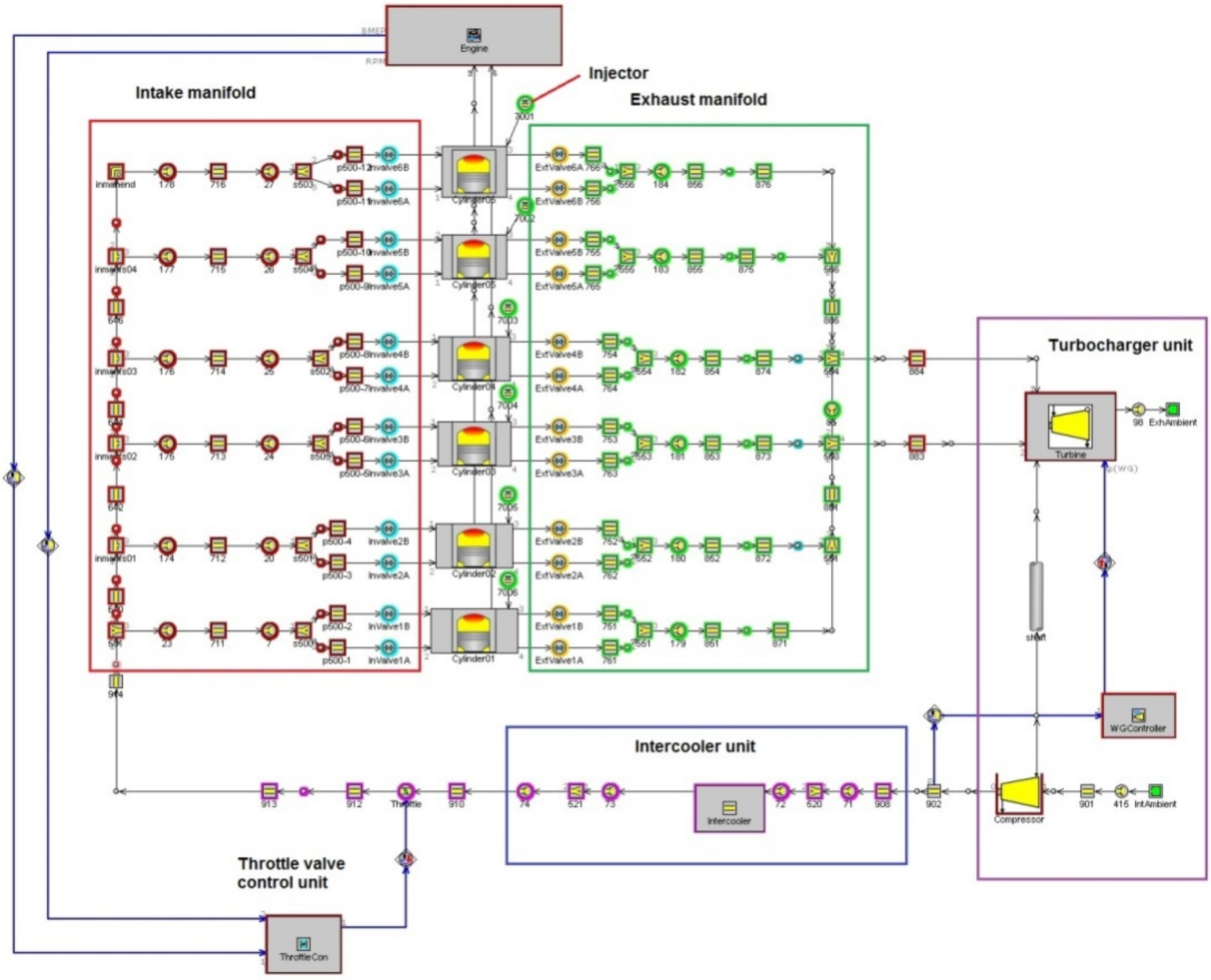

Fig. 1. GT-Power model of the engine.

2.1 *Fuel Properties*

Butanol is a potentially promising biofuel, which could be used conveniently up to high blending ratio with diesel fuel in diesel engines [26]. The fuels used in this study are diesel and butanol. The volume percentages used in the simulation were 5%, 15% and 25% of butanol with 95%, 85% and 75% of diesel fuel, respectively. The properties of diesel and n-butanol used in the study are summarized in Table 2.

The following equations, Equations 1, 2, 3 and 4 were used for modelling the viscosity and thermal conductivity of n-butanol in liquid and vapour phase [30]:

$$\mu_L = E.\exp\left[A\left(\frac{C-T}{T-D}\right)^{1/3} + B\left(\frac{C-T}{T-D}\right)^{4/3}\right] \qquad (1)$$

$$\mu_V = \frac{AT^B}{1+CT^{-1}+DT^{-2}} \qquad (2)$$

$$\mathrm{K}_L = A\left(1+B*\left(1-\frac{T}{T_c}\right)^{1/3} + C*\left(1-\frac{T}{T_c}\right)^{2/3} + D*\left(1-\frac{T}{T_c}\right)\right) \qquad (3)$$

$$\mathrm{K}_V = \frac{\sqrt{\dfrac{T}{T_c}}}{\left(A+\dfrac{B*T_c}{T}+\dfrac{CT_c^2}{T^2}+\dfrac{DT_c^2}{T^3}\right)} \qquad (4)$$

Where μ_L and μ_V are the viscosities of butanol at liquid and vapour phase respectively and K_L and K_V are its thermal conductivity at liquid and vapour phase .A, B, C, D and E are empirical coefficients, T_c is the critical temperature of butanol and T is temperature.

Table 2. Properties of the diesel fuel and butanol [30]-[32].

Fuel properties	Diesel	n-Butanol
Chemical formula	$C_{13.5}H_{23.6}$	C_4H_9OH
Molecular weight [kg/kmol]	185.6	74.12
Density@20C [kg/m^3]	840-880	813
Lower calorific value [MJ/kg]	42.5	33.1
Heat of vaporization [MJ/kg]	0.27	0.581
Cetane number	45-55	17
Stoichiometric air fuel ratio	15	11.9
Oxygen content [wt. %]	0	21.6
Hydrogen content [wt. %)	12.7	13.5
C/H ratio	0.57	0.4
Flash point [˚C]	85	37
Self-ignition temperature [˚C]	>250	385

2.2 Governing Equations

The differential form of the apparent heat release rate is given by (5) [5], [33]:

$$\frac{dQ_n}{d\theta}=\frac{dQcomb}{d\theta}-\frac{dQ_{ht}}{d\theta}=\left(\frac{\gamma}{\gamma-1}\right)P\frac{dV}{d\theta}+\left(\frac{1}{\gamma-1}\right)V\frac{dP}{d\theta} \qquad (5)$$

Where: dQn/dθ is the net heat release rate , $dQ_{comb}/d\theta$ is the heat released by combustion, $dQ_{ht}/d\theta$ is heat transfer rate from the wall calculated on the basis of Woschni correlation, γ is the ratio of specific heats, which is calculated according to an empirical equation, P is the cylinder gas pressure , and V is the instantaneous volume of the cylinder .For this calculation, the contents of the cylinder were assumed to behave as an ideal gas (air), with the specific heat being dependent upon temperature; leakage through the piston rings was neglected.

The in-cylinder pressure [5], [33] of the model was determined using Equation 6:

$$\frac{dP}{d\theta}=\frac{\gamma-1}{V}\left[\frac{dQ_{comb}}{d\theta}-\frac{dQ_{ht}}{dt}\right]-\gamma\frac{P}{V}\frac{dV}{d\theta} \qquad (6)$$

NO_X is produced at a great extent, due to the high local temperatures found in diesel engines which are highly dependent on the initial rise of heat release [5].Although there are various forms of nitrogen based emissions that comprise oxides of nitrogen (NO_X), nitric oxide (NO) makes up the majority of all NO_X emissions produced by the engine. In newer technologies of turbocharged diesel engines, the proportion of NO_2 in total NO_X can be as high as 15% or more. NO_X concentrations in diesel exhaust are typically between 50 and 1000 ppm [34].

The nitric oxide formation model in GT-Power is based on the extended Zeldovich [5] mechanism and is given by Equations 7 to 9:

$$N_2+O \underset{k_1^-}{\overset{k_1^+}{\rightleftarrows}} NO + N \qquad (7)$$

$$N+O_2 \underset{k_2^-}{\overset{k_2^+}{\rightleftarrows}} NO + O \qquad (8)$$

$$N+OH \underset{k_3^-}{\overset{k_3^+}{\rightleftarrows}} NO + H \qquad (9)$$

Where k^+ and k^- are forward and reverse rate constants and are given by Equations 10 to 15, respectively:

$$k_1^+=7.6x10^{13}\exp(-\frac{38000}{T}) \qquad (10)$$

$$k_1^-=1.6x10^{13} \qquad (11)$$

$$k_2^+=6.4x10^{9}\exp T(-\frac{3150}{T}) \qquad (12)$$

$$k_2^-=1.5x10^{9}T\exp(-\frac{19500}{T}) \qquad (13)$$

$$k_3^+=4.1x10^{13} \qquad (14)$$

$$k_3^-=2.0x10^{14}\exp(-\frac{23600}{T}) \qquad (15)$$

3. RESULTS AND DISCUSSION

A simulation was carried out on six cylinders, turbocharged and DI diesel engine using GT-POWER computational simulation tool to investigate the performance and exhaust emissions of blends of n-butanol with conventional diesel fuel, for 5%, 15% and 25% n-butanol diesel blends. The engine's performance and emission characteristics were compared with neat diesel fuel. The results with regard to engine's performance, combustion and emission characteristics are discussed.

3.1 Heat Release Rate, Pressure and Temperature

Heat release rate is an important indicator of combustion efficiency. This particular parameter helps to explain the changes in performance and combustion and emission. There are four phases of conventional diesel engine combustion: ignition delay, premixed or rapid combustion phase, mixing controlled combustion phase, and late combustion phase [5]. Figure 2 illustrates the heat release rate for diesel fuel and the three n-butanol blends at a speed of 1800rpm and engine load of bmep=10.5bar. As it is clearly indicated in the figure the heat release rate decreased slightly with the increase of butanol. In comparison with diesel fuel, the heat release rate decreased by 3.6%, 11.1% and 18.6% for 5%, 15% and 25% butanol-diesel blends, respectively. Among the blends, the lowest heat release rate was obtained from 25% butanol-diesel blend.

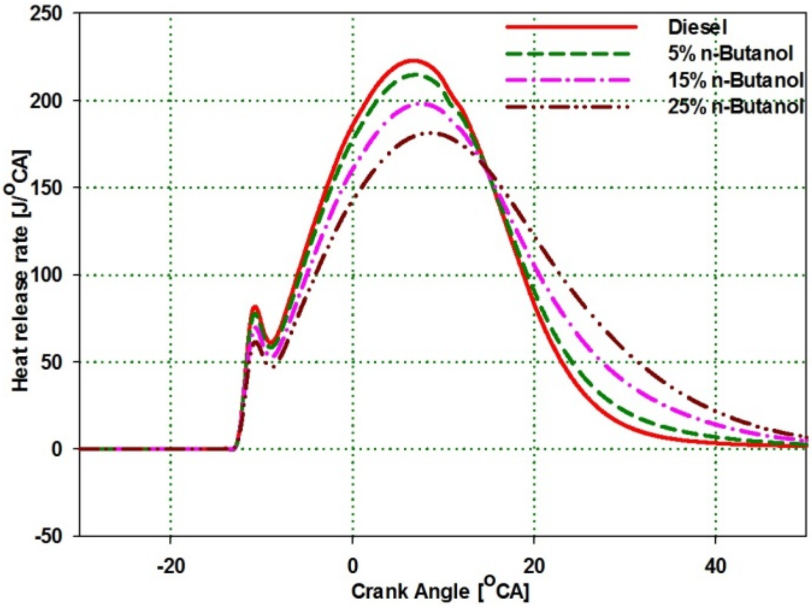

Fig. 2. Heat release rate for diesel fuel and 5%, 15% and 25% butanol blends at a speed of 1800rpm and engine load of brake mean effective pressure of 10.5 bar.

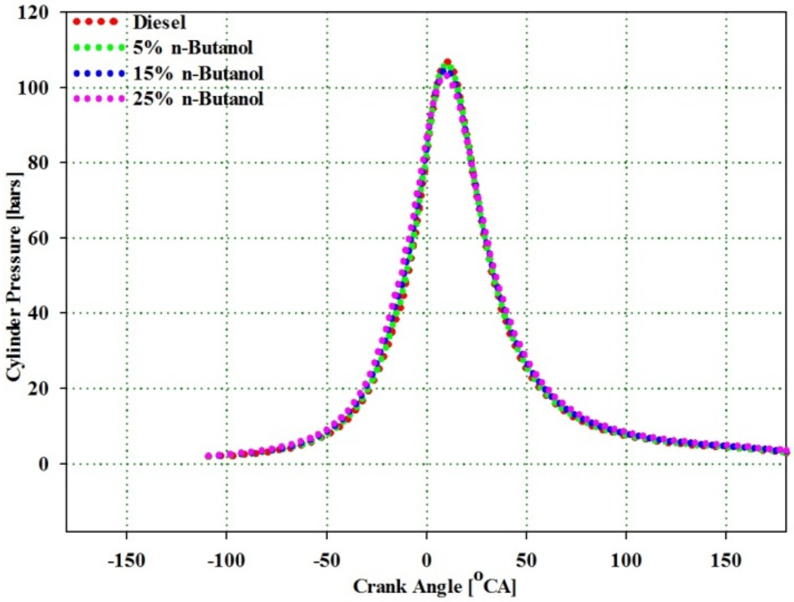

Fig. 3. Combustion pressure for diesel fuel and 5%, 15% and 25% butanol blends at a speed of 1800rpm and engine load of brake mean effective pressure of 10.5 bar.

Both in-cylinder pressure and temperature are important variables that affect the in cylinder mechanical and thermal stresses. Figure 3 depicts the in-cylinder pressure for diesel fuel and butanol-diesel blends at a speed of 1800rpm and engine load of bmep = 10.5 bar. It can be seen that the in-cylinder pressure of the butanol blends are slightly lower than those of the corresponding diesel fuel. The increase in the butanol percentage resulted in a decreased in-cylinder pressure .Compared to diesel fuel; there was a decrease in the in-cylinder pressure by about 0.6%, 1.9%, and 3.3% for 5%, 15% and 25% butanol-diesel blends, respectively. Maximum in-cylinder pressures were 106.3, 104.9, and 103.3 bar for 5%, 15%, and 25% butanol blends, respectively. The in-cylinder pressure of 25% butanol-diesel blend was found lower than those of 5% and 15% butanol-diesel blends at all loads. The decrease in pressure with the increase of butanol percentage is due to the evaporation cooling effect of butanol which resulted in a decreased specific heat ratio thereby decreasing the in-cylinder pressure [35].

Figure 4 shows the maximum in-cylinder temperature for diesel and 5%, 15% and 25% butanol blends at a speed of 1800rpm for various engine loads. As shown in Figure 4 the in-cylinder temperature decreased with the increase of butanol. Among the blends the in-cylinder temperature of 5% butanol blend was the highest that was 2509K at engine load of bmep 4.5bar and that of 25% butanol blend was the lowest it was 1991.8K at engine load of bmep 7.5 bar. In comparison with diesel fuel the maximum in-cylinder temperature decreased by 3.7%, 10.6% and 14.9% for 5%, 15% and 25% butanol blends respectively at an engine load of bmep 10.5 bar. The lower in cylinder temperature of the butanol-diesel blends resulted in a reduced NO_X emissions.

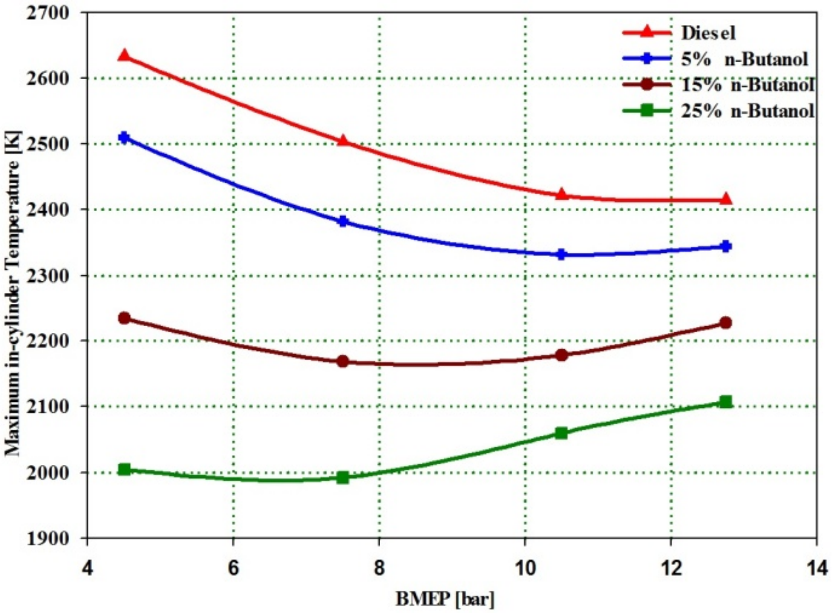

Fig. 4. Maximum in-cylinder temperature for diesel fuel and 5%, 15% and 25% butanol blends at a speed of 1800rpm and engine load of bmep = 6.5, 8.5, 10.5 and 12.75 bar.

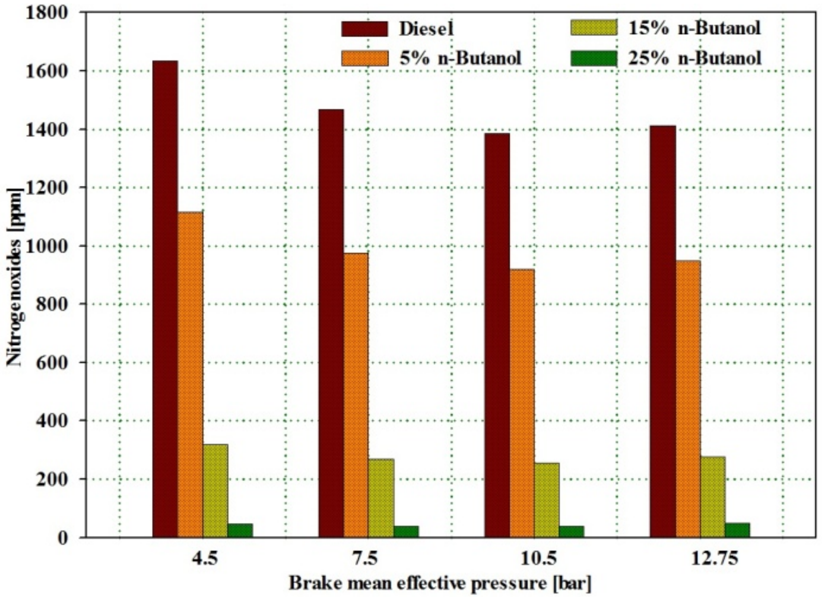

Fig. 5. Nitrogen oxides emissions for diesel fuel and 5%, 15% and 25%butanol blends at four loads and at a speed of 1800 rpm.

3.2 Nitrogendi Oxide Emissions

The formation of NO_X is strongly dependent on oxygen concentration, combustion temperature and residence time of high temperature [36]. Figure 5 shows the NOx emissions of the engine using butanol blended fuels and neat diesel fuel at four different loads at an engine speed of 1800rpm. The peak apparent heat release rate is proportional to the flame temperature. The increase of butanol blends decreased the apparent heat release rate as a result the NO_X emissions decreased. Compared to neat diesel fuel, there was a decrease in NOx emissions by about 33.6%, 81.5%, and 97.1% for 5%, 15% and 25% butanol-diesel blends respectively, at 1800 rpm and bmep of 10.5bar for the same engine running conditions. The NOx emissions of 5% butanol-diesel blend was higher than those of 15% and 25% blends at all loads. The results also showed that the NOx emissions were higher at lower loads. One of the reasons for the decreased NO_X emissions with the addition of butanol is because of its higher latent heat of vaporization that lowered the combustion temperature thereby reducing NO_X formation [35].

Figure 6 depicts the effects of engine speed on the NO_X emissions. It can be seen from Figure 6 that, there was a decrease in NOx emissions by about 32.4%, 80.6%, and 96% for 5%, 15% and 25% butanol diesel blends respectively, at 1800 rpm and bmep of 10.5 bar for the same engine running conditions when compared to neat diesel fuel. The minimum NOx emissions were found 6.27, 1.66 and 0.276g/kW for 5%, 15% and 25% butanol-diesel blends respectively at a speed of 1800 rpm.

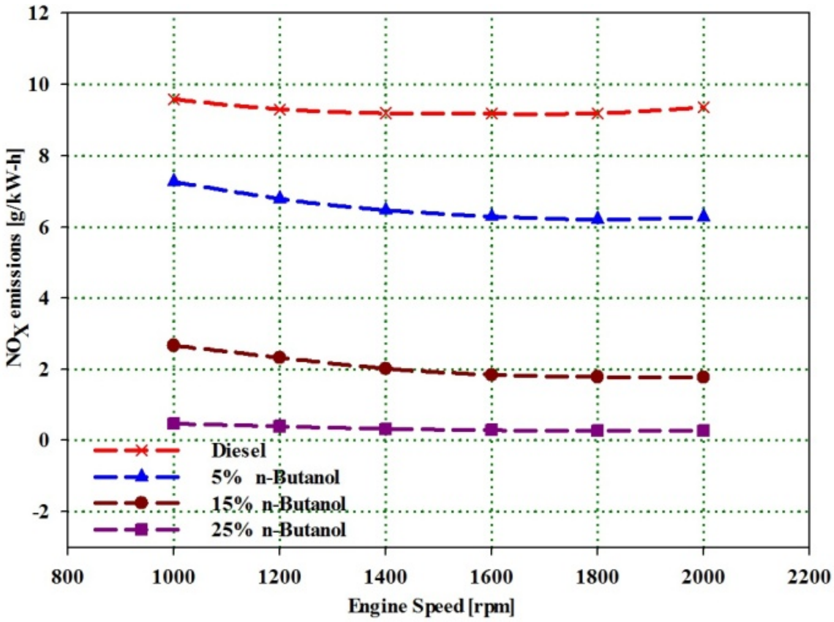

Fig. 6. Effects of engine speed on Nitrogen oxides emissions for diesel fuel and 5%,15% and 25%butanol blends at bmep of 10.5 bar.

3.3 Carbon Monoxide

The rate of CO formation is a function of the available amount of unburned gaseous fuel and of the mixture temperature, both which control the rate of fuel decomposition and oxidation [37]. CO is formed as a result of incomplete combustion of fuel and is generally formed in rich fuel zone due to lack of oxygen. Figure 7 depicts the effects of butanol diesel blends on the CO emissions of the engine. As Figure 7 clearly shows it was found out that the CO emissions of butanol-diesel fuel blends were lower than the corresponding neat diesel fuel operation. The CO emissions decreased significantly with the increase of butanol percentage in the blend. The CO emissions decreased by 13.1%, 41.2% and 71.7% for 5%, 15% and 25% butanol-diesel blends respectively at a speed 1800 rpm and bmep of 10.5 bar when compared to neat diesel fuel. It was observed that the highest decrease in CO emission was about 75.1% for 25% butanol diesel blends at a load of bmep 12.75 bar. The CO emissions for 5% butanol-diesel blends were higher than those of 15% and 25% blends at all load. Many researchers have shown that the addition of biofuels like ethanol and butanol decreases the CO emissions since they have less carbon than diesel fuel and their oxygen content increases the oxygen to fuel ratio in the fuel rich regions, the CO emissions are generally reduced at full load because of the increased air-fuel ratio and more complete combustion [38]-[41].

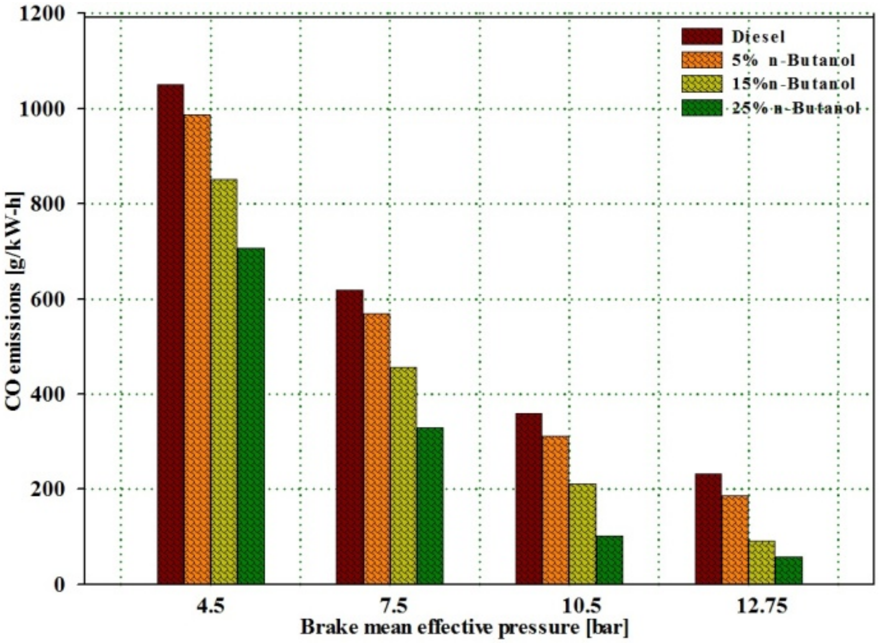

Fig. 7. Carbon monoxide emissions for diesel fuel and 5%, 15% and 25%butanol blends at four loads and at a speed of 1800 rpm.

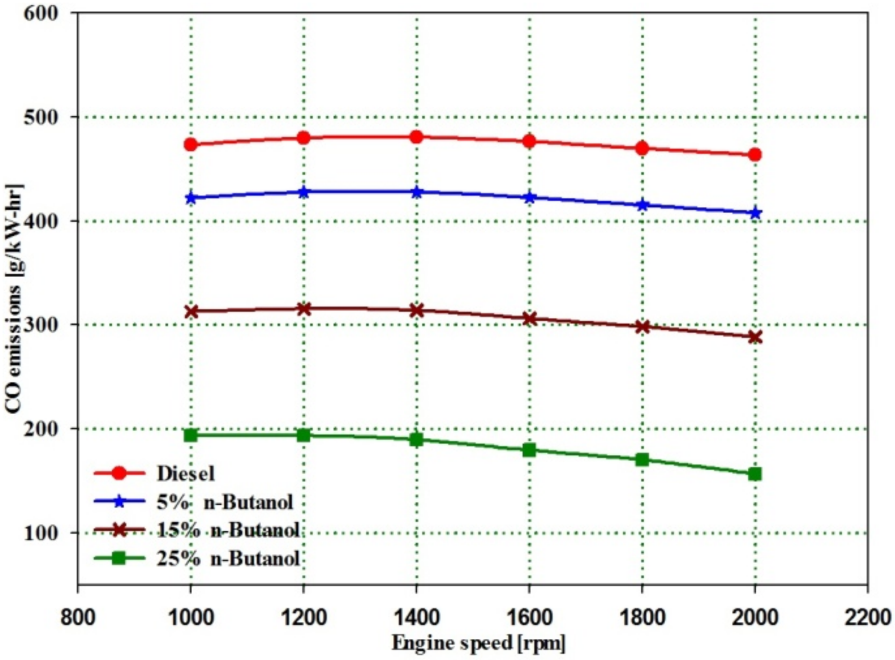

Fig. 8. Effects of engine speed on carbon monoxide emissions for diesel fuel and 5%, 15% and 25%butanol blends at bmep of 10.5bar.

Figure 8 depicts the effects of engine speed on the CO emissions for the different butanol diesel fuel blends. The values of CO in all working conditions decreased with increasing the engine speed as a result of improved combustion process. The CO emissions of 25% butanol diesel blends were the least for all engine speeds when compared with the other blends. The minimum CO emissions were found 407.8, 288.3 and 156.6g/kW for 5%, 15% and 25% butanol-diesel blends respectively at a speed of 2000 rpm.The results also showed that at 1400rpm there was a maximum CO emission for the 5% butanol. The CO emissions decreased by 10.9%, 34.6% and 60.5% for 5%, 15% and 25% butanol diesel blends at 1400 rpm when compared with neat diesel fuel.

3.4. Carbon Dioxide

Figure 9 illustrates the effects of butanol diesel blends on the CO_2 emissions for the given engine. It was found that the CO_2 emissions of butanol-diesel fuel blends were higher than the corresponding neat diesel fuel operation. The results of the simulation showed that the CO_2 emissions increased with increase in load and butanol percentage. The CO_2 emissions increased by 15.1%,48.1% and 84.3% for 5%,15% and 25% butanol-diesel blends respectively at a speed of 1800 rpm and bmep of 10.5 bar when compared to neat diesel fuel. The CO_2 emissions for 5% Butanol-diesel blends were lower than those of 15% and 25% blends at all loads. The CO_2 emissions of 25% butanol-diesel blends were higher by 37.5% and 19.7% than 5% and 15% butanol blends at a load of bmep 10.5bar. The increase in CO_2 emissions can be explained as follows, the use of biofuels allows a higher relative concentration of oxygen to exist in the combustion gases and this resulted in a greater conversion of CO to CO_2 than for diesel fuel [11].

Figure 10 shows the effects of engine speed on the CO_2 emissions for butanol-diesel blends and neat diesel. The CO_2 emissions of all the butanol blends decreased between 1000-1400rpm and increased after 1400rpm.The CO_2 emissions for 5% butanol-diesel blends were lower than those of 15% and 25% blends at all loads. It was also observed that CO_2 emissions of 25% butanol diesel blends were the highest at all engine speeds. For example, the CO_2 emissions were higher by 38.3% and 20.3% than 5% and 15% butanol diesel blends at 2000rpm. The minimum CO_2 emissions were found 494.57g/kW-h for 5% blends at a speed of 1400rpm and 640.8 and 802.2g/kW-h for 15% and25% butanol-diesel blends respectively at a speed of 1200rpm. The CO_2 emissions were maximum at 2000rpm, it increased by 15.9%, 50.6% and 89% for 5%, 15% and 25% butanol-diesel blends when compared with neat diesel fuel.

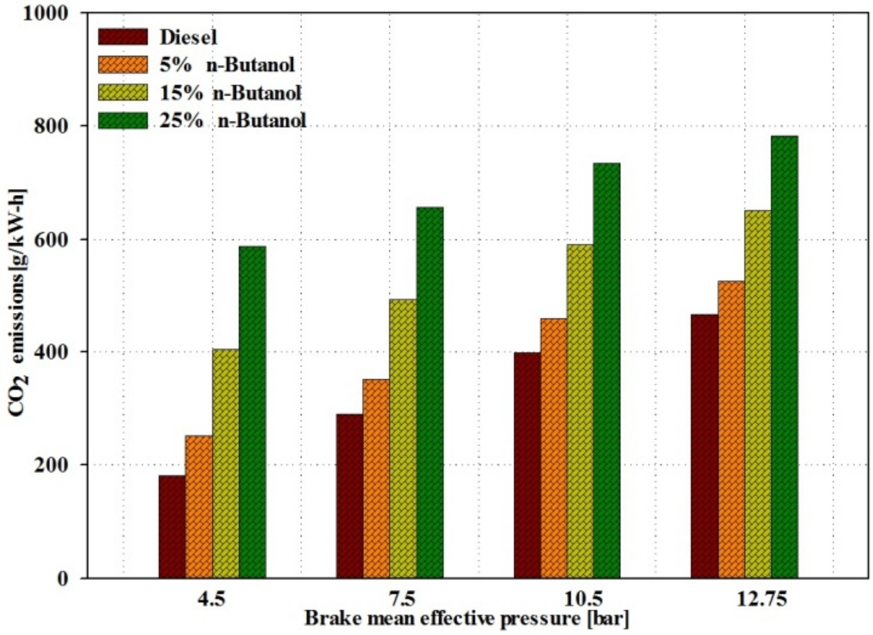

Fig. 9. Carbon dioxide emissions for diesel fuel and 5%, 15% and 25%butanol blends at four loads and at a speed of 1800 rpm.

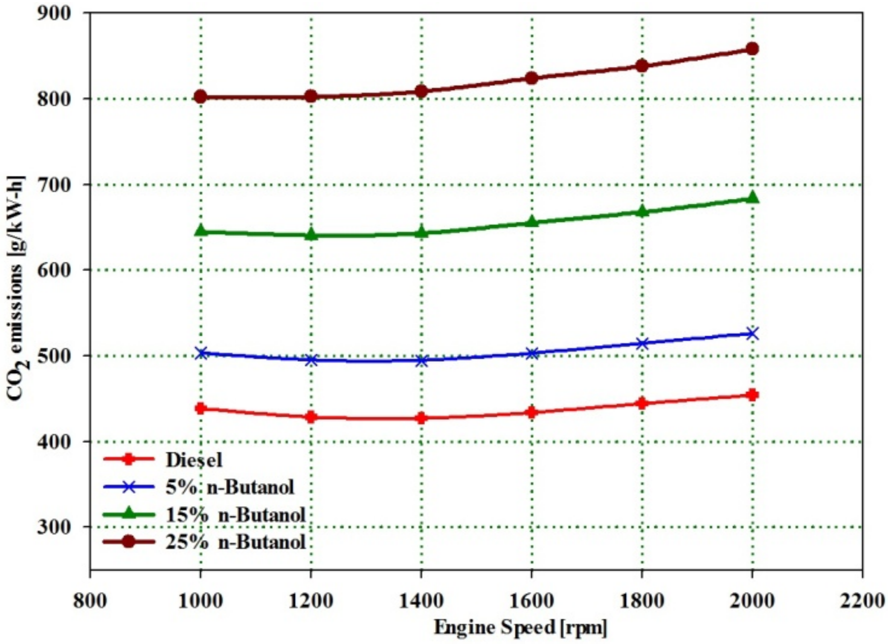

Fig. 10. Effects of engine speed on Carbon dioxide emissions for diesel fuel and 5%, 15% and 25%butanol blends at bmep of 10.5 bar

3.5 Unburned Hydrocarbon

Hydrocarbons or, more appropriately, organic emissions are the consequence of incomplete combustion of hydrocarbon fuel [5]. The variation of the indicated specific HC emissions for different butanol-diesel blends and neat diesel is shown in Figure 11. The results showed that the HC emissions of the butanol-diesel fuel blends were higher than the corresponding neat diesel fuel operation at all engine operating conditions. For instance, the HC emissions were higher by 4.7%, 13.5% and 21.3% for 5%, 15%and 25% butanol-diesel blends at 1800rpm and engine load of bmep 10.5 bar. It was observed that the HC emissions of 25% butanol diesel blends were higher than those of 5% and 15% butanol diesel blends at all loads. The HC emissions were minimum at higher engine loads for instance at 12.75bar of bmep it was found that the HC emissions were 0.1209, 0.1315 and 0.1405 ppm for 5%, 15% and 25% butanol diesel blends respectively. The reason for the increased HC emissions with the addition of butanol is due to the higher heat of evaporation of the butanol blends causing slower evaporation and slower and poorer fuel–air mixing, to the increased spray penetration causing unwanted fuel impingement on the chamber walls [5], [6].

Figure 12 depicts the effects of engine speed on the HC emissions for the different butanol diesel fuel blends at 10.5 bar of bmep. It was found that the HC emissions of the blends were higher than neat diesel fuel at all operation conditions. The HC emissions decreased with increasing the engine speed for all the working conditions. It was observed that the HC emissions of 5% butanol diesel blend was the lowest at all engine speeds when compared with other blends. The HC emissions increased by 0.5%, 1.29% and 1.85% for 5%, 15% and 25% butanol-diesel blends at 1000 rpm when compared with neat diesel fuel.

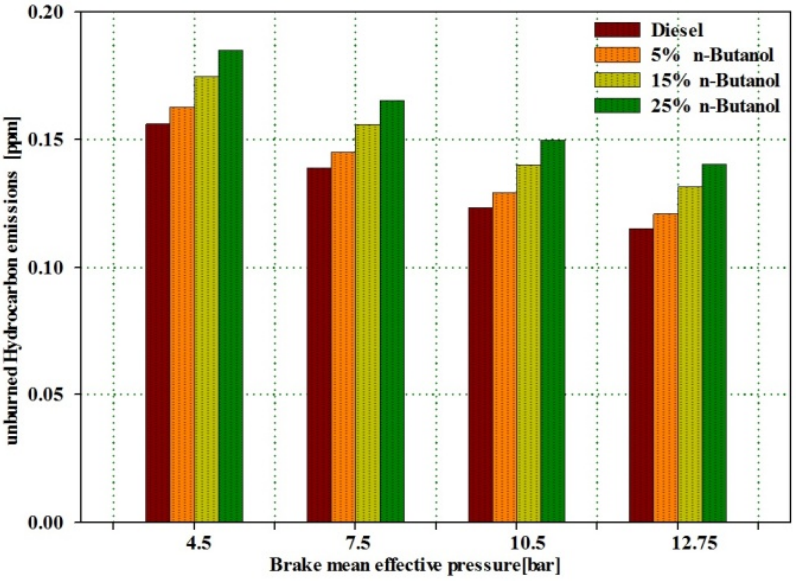

Fig. 11. Hydrocarbon emissions for diesel fuel and 5%, 15% and 25%butanol blends at four loads and at a speed of 1800 rpm.

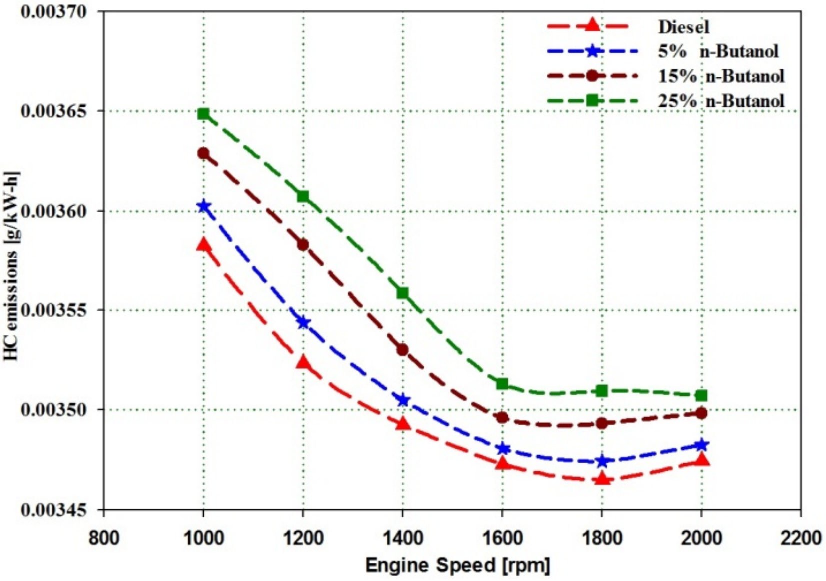

Fig. 12. Effects of engine speed on HC emissions for diesel fuel and 5%, 10% and 25% butanol blends at bmep of 10.5 bar.

3.6 Exhaust Temperature and Brake Thermal Efficiency

Figure 13 shows the exhaust gas temperature of the engine at various load conditions for diesel and the different butanol-diesel blends. The exhaust temperature showed a slight increase with the addition of butanol. Compared to the neat diesel fuel operation; the exhaust gas temperature increased slightly for engine loads of 4.5, 7.5 and 10.5 bar except for 12.75 bar. It was observed that higher exhaust gas temperatures occurred at higher loads when the engine was run separately on neat diesel fuel and butanol diesel blends. The maximum exhaust gas temperatures were 990.5K, 988.6K and 976.3K when the engine was run on 5%, 15% and 25% butanol-diesel blends, respectively at 1800 rpm and12.75 bar of bmep according to the simulation results.

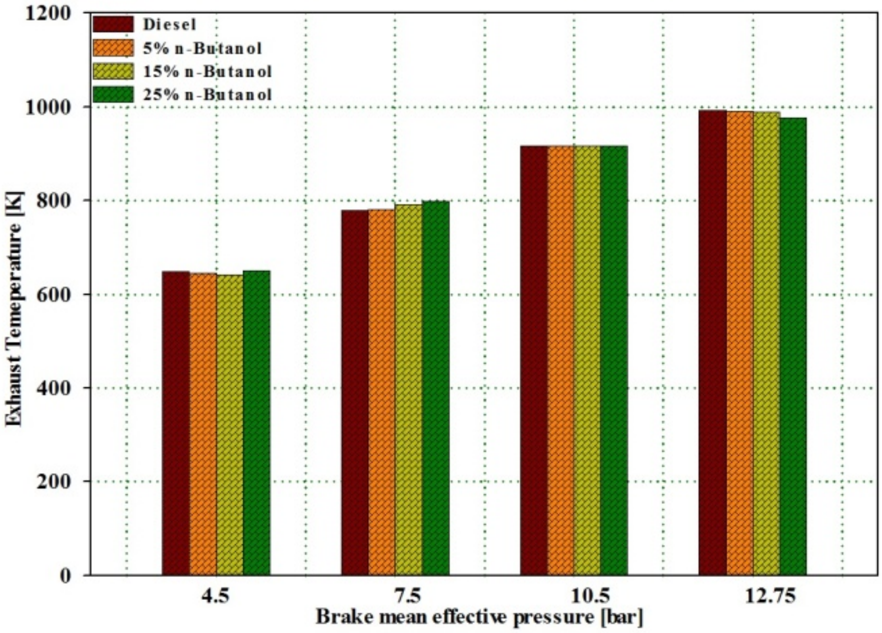

Fig. 13. Exhaust temperature for diesel fuel and 5%, 15% and 25% butanol blends at four loads and at a speed of 1800 rpm.

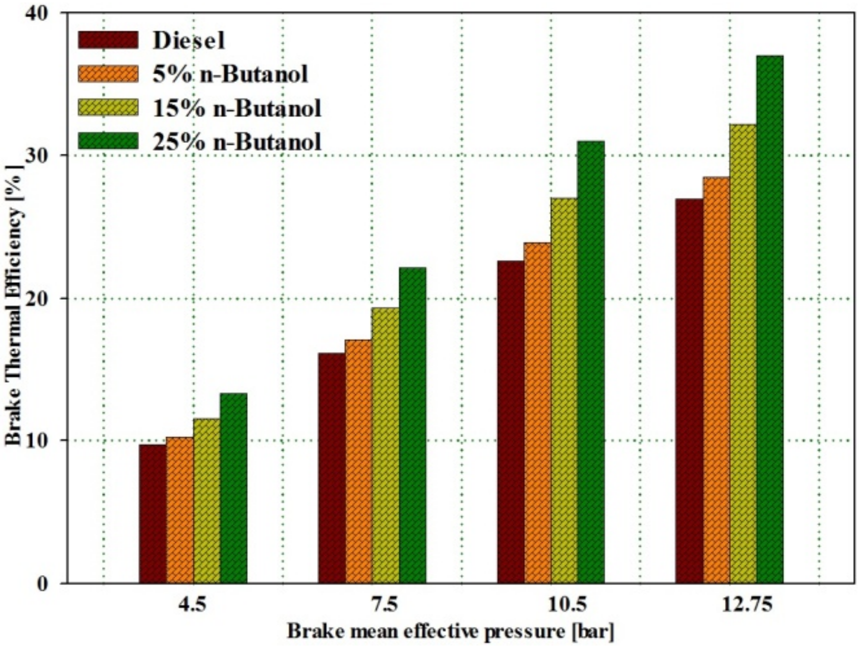

Fig. 14. Brake thermal efficiency for diesel fuel and 5%, 15% and 25% butanol blends at four loads and at a speed of 1800 rpm.

Figure 14 depicts the effects of butanol-diesel blends on BTE of the engine. Simulation results showed the BTE increased with the increase in butanol-diesel fuel blends. It was found that at 1800rpm and 12.75bar of bmep the BTE increased by 5.7%, 19.4% and 37.4% for 5, 15 and 25% butanol-diesel blends respectively when compared to neat diesel fuel. The engine achieved maximum value of BTE that was 37% when run on 25% butanol diesel-blend at 1800 rpm and 12.75 bar of bmep. The increase in BTE can be explained as follows: due to the higher content of oxygen in butanol resulted in a more complete combustion in the fuel rich zone thereby improving the combustion efficiency. Moreover, heat losses decrease in the cylinder due to lower flame temperature of butanol than that of neat diesel fuel [42]. As shown in Figure 15 the results showed that the heat transfer coefficient for the blends was lower when compared with neat diesel fuel that was the reason for decreased heat losses and increased BTE.

Figure 16 shows the brake specific fuel consumption (BSFC) for the neat diesel fuel and the various percentages of the butanol-diesel. It was observed that for all the butanol–diesel fuel blends, the bsfc was lower than that for the corresponding neat diesel fuel. It was found that at 1800rpm and 10.5 bar of bmep the bsfc decreased by 4.9% ,14.9% and 25% for 5,15 and 25% butanol-diesel blends respectively when compared to neat diesel fuel. As seen in figure 25% butanol-diesel blend has the lowest bsfc among the blends.

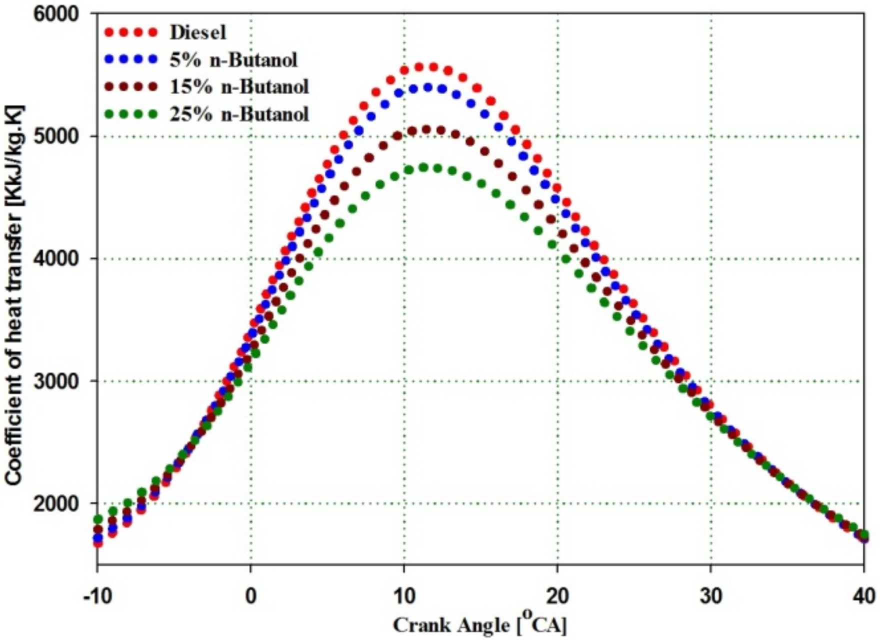

Fig. 15. Coefficient of heat transfer for diesel fuel and 5%, 15% and 25% butanol blends at four loads and at a speed of 1800 rpm.

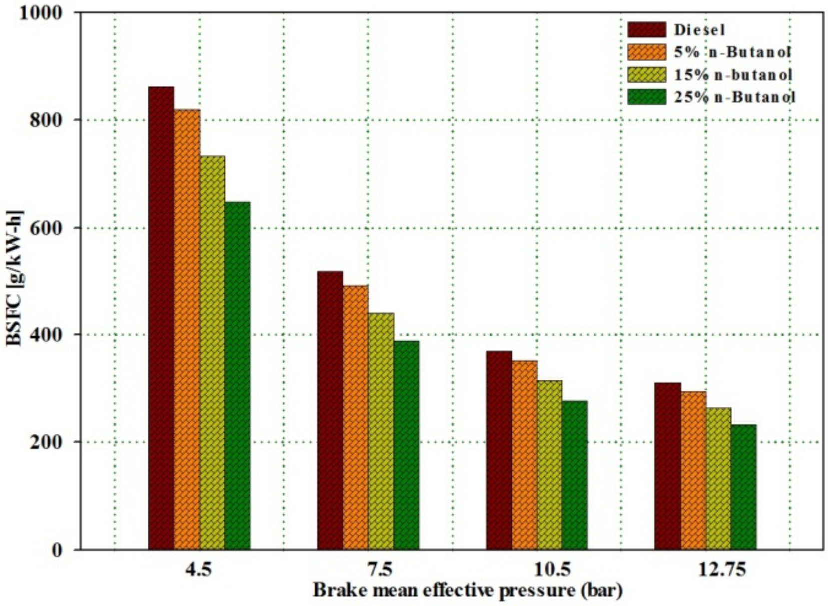

Fig. 16. Brake specific fuel consumption for diesel fuel and 5%, 15% and 25%butanol blends at four loads and at a speed of 1800 rpm.

4. CONCLUSIONS

It was observed that the brake thermal efficiency improved with butanol-diesel fuel blends when compared with the diesel fuel case. The BTE improved significantly with the increased butanol percentage at the same operation condition. Its value improved by more than 20% for butanol-diesel blends when compared with diesel fuel operation.

It was found that NOx emission reduced significantly for butanol-diesel fuel blends. NOx emissions decreased by average more 70% when using butanol-diesel blends.

Up to a 40% reduction in CO emission was possible with the use of butanol diesel blends as compared to neat diesel alone. However, CO_2 and unburned hydrocarbons emissions increased by 45% and 14%respectively during butanol diesel fuel operation .Taking the results of the simulation into consideration due to its optimum performance and emission values 15% butanol blend was the best choice for the engine.

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