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An Investigation of Diesohol-Biodiesel Mixture in Performance-Emission Characteristics of a Single Cylinder Diesel Engine: A Trade-Off Benchmark

S. Dey[1*], M. Deb[2] and P. K. Das[2]

[1]Mechanical Engineering Department, National Institute of Technology Agartala, 799046, India
[*]Email: suman2013mech@gmail.com
[2]Mechanical Engineering Department, National Institute of Technology Agartala, 799046, India

ABSTRACT

The issue of environmental pollution and the depletion of fossil fuel are nowadays a major field of attention for the modern world. In substitution of petroleum-based diesel, biodiesel and ethanol have been explored in many studies. In this paper, diesel-palm biodiesel-ethanol has been used together at different proportion to execute performance-emission characteristics and their trade-off study at different brake power. An experimental investigation is carried out for different diesel-palm biodiesel-ethanol blends ranging by volume of 5-10% ethanol, 5-25% biodiesel and 65-90% baseline diesel. From the experimental results, comparatively, low brake specific fuel consumption (BSEC) has been observed for all 5% ethanol-blended fuels. Maximum reduction in BSEC has been observed 1.9, 2, and 3.24 % at 0.68, 2.05, and 3.42 kW respectively. At medium to high load, brake thermal efficiency (BTE) has been found higher for lower ethanol fraction. As compared to diesel, the highest nitrogen oxide (NOx) reduction have been found 13.7, 9.17, and 4.7 % at 0.68, 2.05, and 3.42 kW respectively. At last, performance-emission trade-off shows that D70B25E5 blend has a higher BTE with maximum reduction in unburnt hydrocarbon (UHC) and NOx emissions.

Keywords: Alternative energy; blend preparation; performance-emission; NOx-BSEC-BTE trade-off; NOx-UHC-BTE trade-off.

NOMENCLATURE

CO	carbon monoxide	DAQ	data acquisition
ITE	indicated thermal efficiency	DE	diesel ethanol
BE	biodiesel ethanol	VCR	variable compression ratio
BTE	brake thermal efficiency	GUI	graphical user interphase
NOx	nitrogen oxides	HRR	heat release rate
MME	mahua methyl ester	BSNOx	brake specific oxides of nitrogen
UHC	unburned hydrocarbon	D100	100% diesel
BSFC	brake specific fuel consumption (kg/kW-h)	D90B5E5	90% diesel+5% biodiesel+5%ethanol
BSEC	brake specific energy consumption (kJ/kW-h)	D85B10E5	85% diesel+10% biodiesel+5%ethanol

D80B10E10	80% diesel+10% biodiesel+10%ethanol	D80B15E5	80% diesel+15% biodiesel+5%ethanol
D75B15E10	75% diesel+15% biodiesel+10%ethanol	D75B20E5	75% diesel+20% biodiesel+5%ethanol
D70B20E10	70% diesel+20% biodiesel+10%ethanol	D70B25E5	70% diesel+25% biodiesel+5%ethanol
D65B25E10	65% diesel+25% biodiesel+10%ethanol	D85B5E10	85% diesel+5% biodiesel+10%ethanol

INTRODUCTION

The rapid rise in crude oil price due to its vast application in factory, transportation, agriculture etc. have been increasing day by day. Most of the modern engine works on diesel operation where the application of diesel in transportation has recorded the highest emissions. The ever-increasing concern of environment pollution is mainly due to the dreadful level of greenhouse gas emissions worldwide [1]. Among all the greenhouse gas emissions, NOx and particulate matter (PM) are more predominant in environment pollution. Now, most of the countries have transformed their thought towards alternative energy resources where animal fat, vegetable oil-based biodiesel and alcohol play a vital role. Moreover individually biodiesel or alcohol cannot perform effectively due to their poor physiochemical property [2]. Due to poor properties, lubricating oil in biodiesel fuelled engine has faced an increase in density, carbon residue and ash content with the usage [3]. Experimentally it has been found that biodiesel containing free fatty acid when mixed with diethyl ether has improved acid value, heating value and pour point [4]. Transesterification [5] is a technique for high viscous biodiesel to prevent problems like formation of carbon deposits in the combustion chamber, fuel filter plugging, injector coking, ring sticking and contamination of lubricating oil [6] etc.

Diesel fuel replaced by Jatropha, Moringa and Palm biodiesel up to 20% based on ASTM D6751 standard has improved performance and emissions without any engine modification [7]. Blending of alternative fuels in the form of diesel-ethanol, biodiesel-ethanol or diesel-biodiesel-ethanol is environment-friendly and less toxic [8][9][10][11]. Also, long-chain alcohol like pentanol when mixed with diesel can improve the thermophysical property of the blend. Superior combustion due to enriched oxygen in diesel-pentanol blend improves BSFC (brake specific fuel consumption) and BTE [12]. Higher BTE has been found for ethanol-diesel blend compared to base diesel. BTE also increases at all load condition due to the addition of cetane number improver that helps further to reduce NOx and smoke emission [13]. However, to produce optimum performance-emissions of the engine appropriate mixture of the additive is the key concern [14]. High oxygen content biodiesel of poor cold flow property, high density and pour point create a barrier while performing in cold weather condition. Ethanol or diethyl ether is one of the substitutes to meet the desired properties of biodiesel for use in the diesel engine. Addition of ethanol in palm biodiesel-diesel blend enhanced kinematic viscosity, cloud and pour point of the blend [15]. Ethanol commonly known as alcohol produced from sugarcane, corn, sugar beet, molasses etc. helps in reduction of PM emission due to the presence of high oxygen molecules [16][17]. Experimentally it has been found that with increasing ethanol fraction in the ethanol-biodiesel blend, pressure and heat release rate (HRR) increases. Also due to the higher latent heat of vaporisation of ethanol, BSNOx (brake specific nitrogen oxides) emission decreases [18].

Experiment on naturally aspirated, 4-cylinder direct-injection diesel engine using ultralow sulfur diesel as base fuel with biodiesel and ethanol as an additive improved BTE. High oxygen content in additive reduces both HC (hydrocarbon) and CO (carbon monoxide) emissions compared to base diesel whereas NOx emission increases [19]. At different advanced injection timing, as ethanol fraction increases on a biodiesel-ethanol blend, NOx emission decreases at medium to high load. Due to the low heating value of ethanol, as percentage addition increases, it increases ignition delay that results in lower peak cylinder pressure and temperature [20]. High viscosity Mahua Methyl Ester (MME), when blended with ethanol, improves the cold flow property of the blend. High latent heat of vaporisation of ethanol also reduced combustion temperature that helps in lowering the NOx emission. Also, prolonged ignition timing due to ethanol helps to reduce smoke emission [21]. The addition of ethanol in biodiesel blended diesel fuel increased HC emission with the increase in ethanol fraction. It has been observed that with the increase in ethanol percentage, the total cetane number of the blend decreases. Slow vaporisation and poor oxidation reaction retard the combustion that results in high HC emission [22]. Study of performance and emissions of a diesel engine at different ethanol fraction where diesel-ethanol blend performed maximum indicated thermal efficiency (ITE) of 35% compared to biodiesel-ethanol blend. Increase in NOx emission with the increase in ethanol is higher in diesel-ethanol (DE) blend than that of biodiesel-ethanol (BE) however CO emission decreases for both blends [23].

Motivation and Objective

Universal currency handled by energy is the main origin of our everyday life necessity. Development of sustainable society by renewable energy phasing referred from the paradigm shift of fossil fuel energy. To support the future energy crisis and high environmental emission, alternative fuel for diesel engine has to be taken care off. There should be required enormous effort in the field of automotive research for more and more green combustion. In the prospect of diesel fuel emission norms, renewable resources like biodiesel or other additives containing oxygenated property can be an effective alternative. The present study provides an interpretive overview of palm biodiesel application on performance-emission characteristics to meet forthcoming challenges in the diesel engine. Palm oil with large oil yield of 4 to 5 tons of oil/ha annually, is ten times higher than soybean, sunflower or rapeseed oil. Easy availability and 20-30% lower production cost compared to other vegetable oils make it the most advantageous alternative to diesel. This paper explains the potential of combined ethanol and palm biodiesel on performance and emissions of single-cylinder 4-stroke diesel engine. This paper also presents NOx-BSEC-BTE and NOx-UHC-BTE trade-off challenges in order to show overall improved performance-emissions synergy by the penalty of any of the emission mandates.

EXPERIMENTAL METHODOLOGY

The experimental investigation is performed at a constant speed (1500 rpm) in a single cylinder 4 strokes, water-cooled, VCR direct injection diesel engine coupled with eddy current dynamometer. The schematic diagram and specification of the engine are shown in Figure 1 and Table 1 respectively. NI Labview® based centralised DAQ is connected to the engine via a computer system which is synchronized with a crank angle encoder onto a GUI based Engine Soft post-processing software. At every 1-degree crank interval, in-cylinder pressure and fuel injection pressure data are measured in DAQ by a piezoelectric pressure sensor (make Kistler). The specific fuel consumption is carried out in fuel burette for a time interval of 60 sec. Air mass flow rate has been calculated by manometric depression integrated into the airbox. A 5-gas analyser (Make: AVL India, Model: 444) with DiGas sampler (Table 2) is fitted at the exhaust pipe to measure the emission of CO, carbon dioxide (CO2), oxygen (O2), NOx and UHC. The gas analyser has been calibrated before each measurement using reference gases to make sure the accuracy of the measured values. For all settings, the emission values and the other values are recorded twice and a mean of these is taken for comparison. The average ambient temperature, cooling water temperature and relative humidity during experimentation is recorded at 25°C, 18°C, and 55%, respectively.

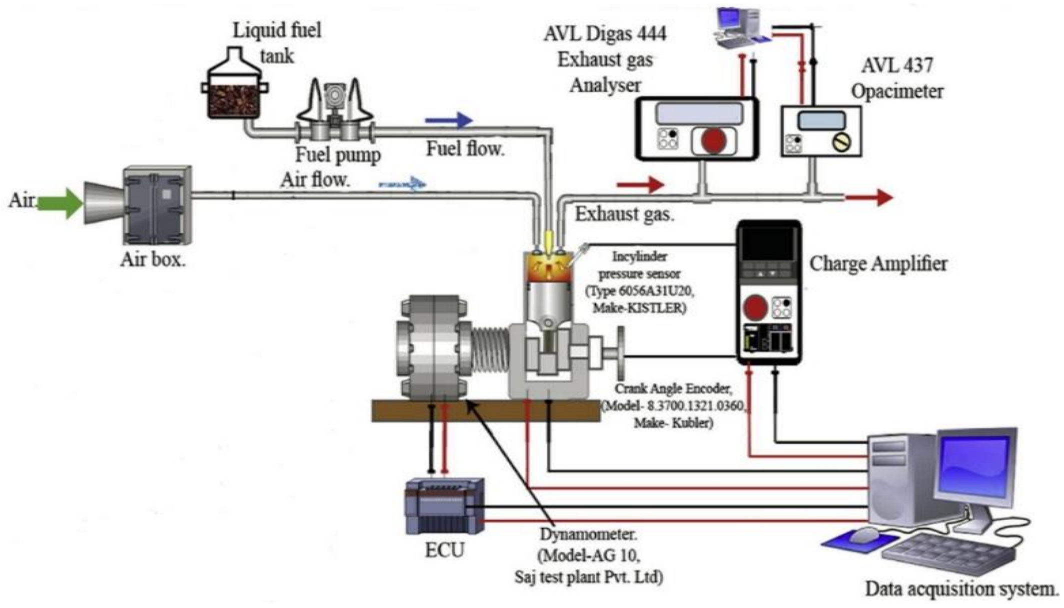


Figure 1. Schematic diagram of the test engine.

Table 1. Specification of the engine.

Serial no.	Parameters	Specification
1	General details	Single cylinder, VCR, 4 stroke, CI engine, vertical, water-cooled, constant speed, direct injection
2	Stroke	110 mm
3	Bore	87.5 mm
4	Displacement	661 cc
5	Compression ratio	17.5
6	Rated output	3.5 kW
7	Rated speed	1500 rpm
8	Fuel injection pressure	220 bar

Data Uncertainty Analysis

Experimental uncertainty analysis is a technique to identify and quantify error during the measurement of emission and the obtained engine performance parameter on account of calibration and utilization of employed instruments, the accuracy of observation and the methodology adopted during experimentation in a given ambient condition. The uncertainty analysis has two main components namely, bias related to accuracy and random variation that occurs during repeated measurements. In this present study, the experimental error analysis which has already been detailed in communication made by the authors in earlier manuscripts [24][25].

Table 2. Accuracy of the emission measuring instrument (AVL DIGAS 444-5 gas analyser) [24].

Measured parameter	Measurement principle	Measuring range	Resolution	Accuracy	%uncertainty in sampling
CO	NDIR	0…10% vol	0.01% vol	<0.6% vol: ±0.03% vol. ≥0.6% vol.: ± 5% of value	±0.2 ± 0.3
CO2	NDIR	0…20% vol.	0.1% vol.	<10% vol.: ±0.5% vol. ≥10% vol.: ±5% of value	±0.15 ±0.2
total unburnt hydro carbons (TUHC)	NDIR	0…20,000 ppm vol. (n-hexane equivalent)	≤2000:1 ppm vol. >2000:10 ppm vol.	<200 ppm vol.: ±10 ppm. ≥200 ppm vol.: ±5% of value	±0.1 ±0.2
O2	Electro chemical sensor	0…22%vol	0.01% vol.	<2% vol.: ±0.1%vol ≥2% vol.: ±5% of value.	±0.2 ±0.3
Nitric oxide (NO)	Electro chemical sensor	0…5000 ppm vol.	1 ppm vol.	<500 ppm vol.: ±50 ppm vol. ≥500 ppm vol.: ±10% of value	±0.2 ±0.9
Lambda		0 … 9.999	0.001		
Warm uptime		≈7 min			
Response time		≤15 s			
Relative humidity		≤95% non-condensing			
PC Interfaces		RS232C			

Preparation of Test Fuel

In this present study, diesel, palm biodiesel, and ethanol blend are used for the performance-emissions test of a diesel engine. The properties of test fuel are shown in Table 3. Diesel is blended with palm biodiesel and ethanol to obtain a ternary blend of different proportion. Preparation of blend is made for 5% and 10% volume of ethanol. Biodiesel is mixed 5, 10, 15, 20 and 25% in volume and subsequent diesel. The prepared blend is denoted by D90B5E5 where D, B, and E denotes diesel, biodiesel, and ethanol and the subsequent number shows their respective volume in percentage. To find the miscibility of ethanol, it has been mixed at different proportion with diesel and palm biodiesel is shown in Figure 2. After keeping all the blends under complete observation for 30 days, the stability of samples is examined. It has been observed from Figure 2 that 5% and 10% ethanol with 95% and 90% diesel were partially non-miscible. Considering the stability of ethanol, D90B5E5, D85B10E5, D80B15E5, D75B20E5, D70B25E5, D85B5E10, D80B10E10, D75B15E10, D70B20E10 and D65B25E10 are selected for the engine test. Using D100 and ten different ternary blends, performance and emissions analysis is carried out for three different brake power (i.e. 0.68, 2.05 and 3.42 kW). At the end, performance-emission trade-off between NOx-BSEC-BTE and NOx-UHC-BTE have been explained. During the experiment, the engine is allowed to run for 10-15 minutes to come to its original working condition. For the consideration of final data of each experimental fuel, an average of six consecutive reading is taken.

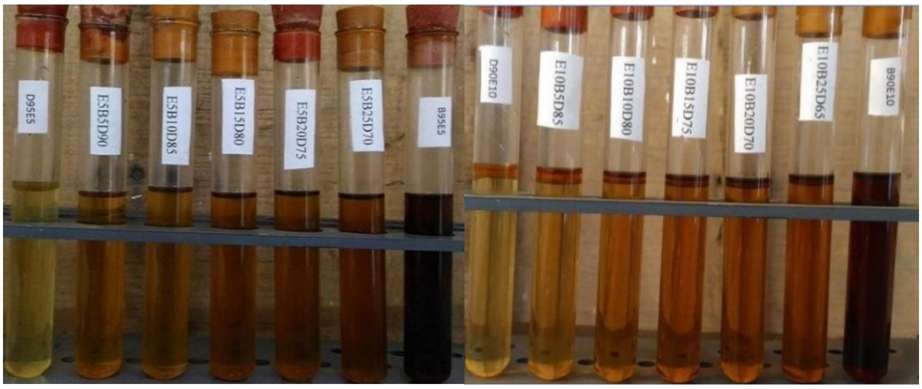


Figure 2. Fuel blends after 30 days.

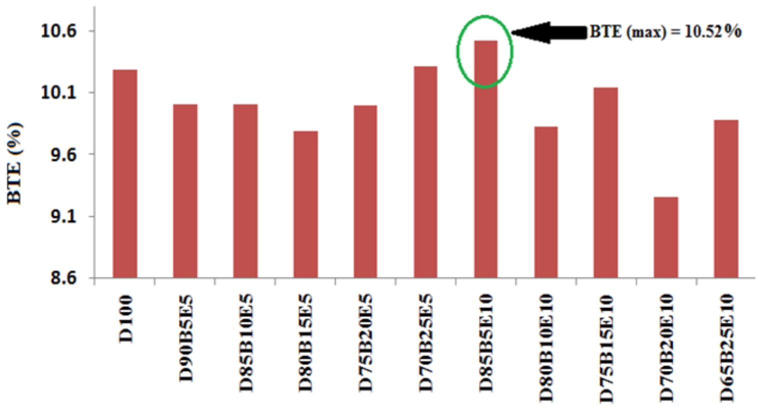
Table 3. Properties of fuel.

	Density at 200C (kg/m3)	Cetane number	Kinematic viscosity at NTP (cSt)	Oxygen content (wt %)	Calorific value (kJ/kg)	Flash point (°C)
Diesel	836	49	2.45	0	42800	100
Palm Biodiesel	925	62	4.56	11.2	39849	167
Ethanol	789	8	1.09	34.8	29700	16.60

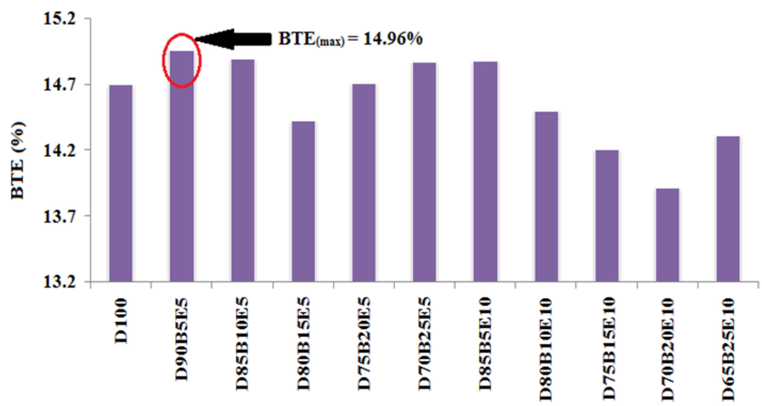
RESULTS AND DISCUSSION

Brake Thermal Efficiency

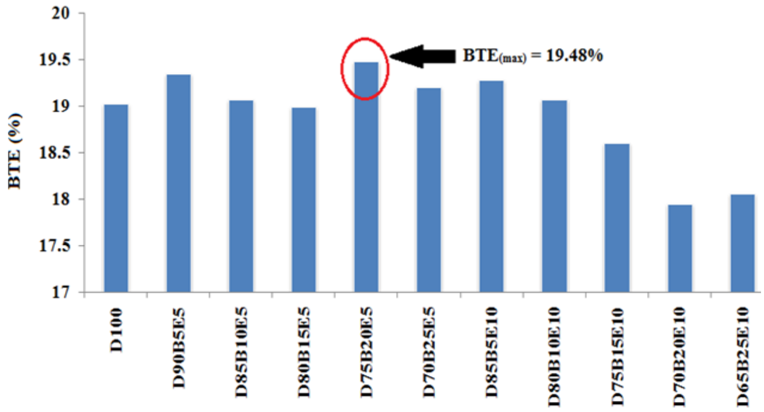
BTE is the evaluation of how well an engine can convert fuel energy into mechanical energy. Figure 3(a)-3(c) show change in BTE at different brake power (BP). It has been found that with increasing BP, BTE increases for all test fuels. Maximum BTE of 10.52, 14.96 and 19.48% has been observed at 0.68, 2.05 and 3.42 kW load for D85B5E10, D90B5E5 and D75B20E5 blend respectively. It can be explained that high oxygen participation and superior mixing enhanced combustion performance that leads to maximum BTE for D85B5E10, D90B5E5 and D75B20E5. At 0.68, 2.05, and 3.42 kW brake power, BTE increases 2.33, 1.8, and 2.4 % for D85B5E10, D90B5E5 and D75B20E5 respectively. It has also been observed that if ethanol percentage increases from 5 to 10%, BTE decreases for all load condition. Among all blend, D90B5E5 shows almost equal BTE as compared to diesel at all load condition. Ethanol has high oxygen content, but low cetane number and heating value. Due to the low cetane value of ethanol, the overall cetane number of the blend decreases. It further decreases the combustion performance that results in low overall thermal efficiency compared to diesel [19].



(a) 0.68 kW



(b) 2.05 kW

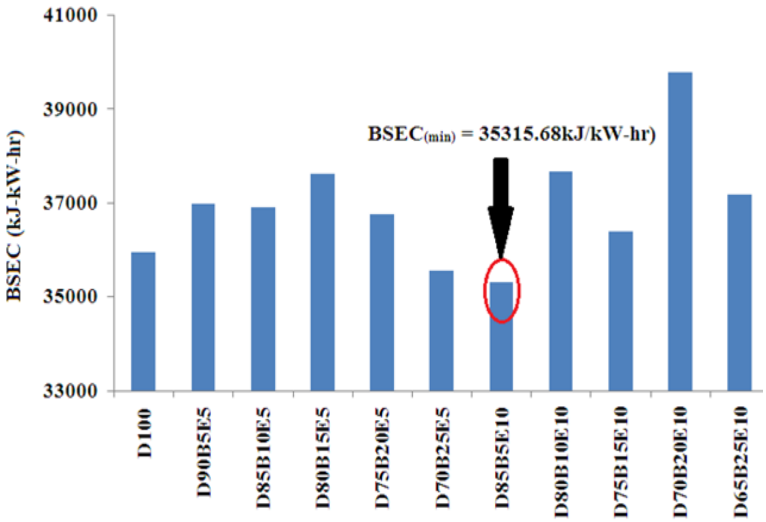


(c) 3.42 kW

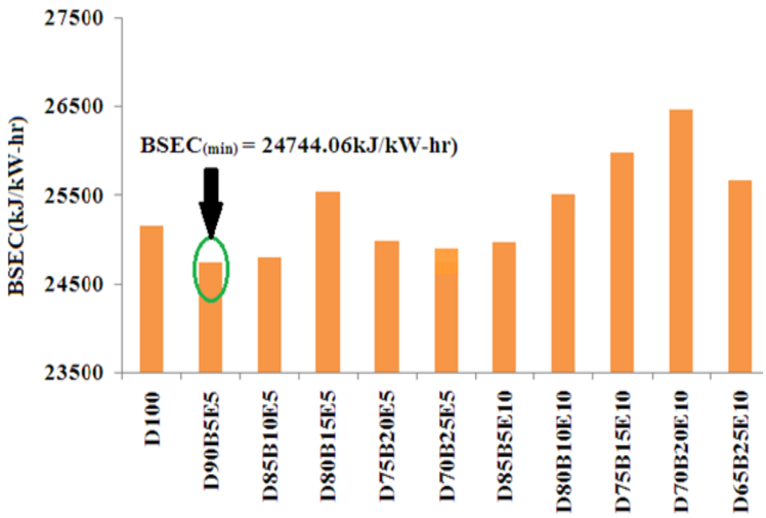
Figures 3. BTE at different brake power.

Brake Specific Fuel Consumption

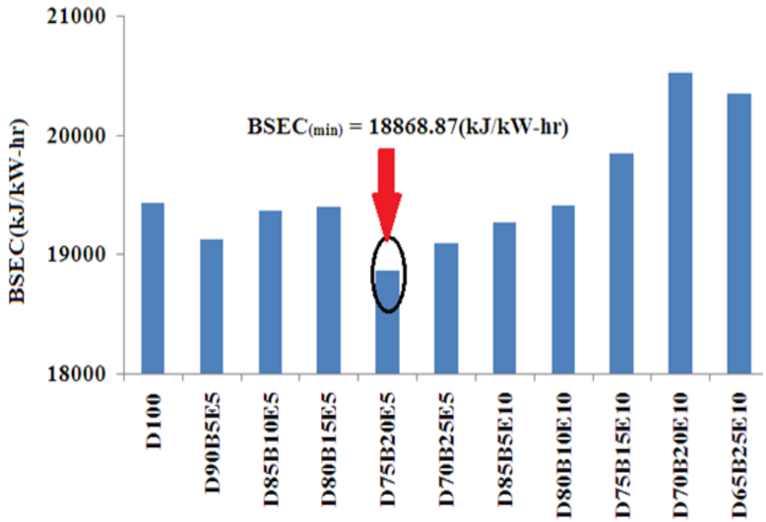
BSEC implies the efficiency of fuel energy which is effective during combustion for engine output. Figure 4(a)-4(c) depict the variation of BSEC (kJ/kW-h) with brake power for all test fuels, where, as brake power increased BSEC of fuel decreases. Lowest BSEC at 0.68, 2.05 and 3.42 kW brake power have been found for D85B5E10, D90B5E5 and D75B20E5 blend respectively. The lowest BSEC at 0.68, 2.05, and 3.42 kW are marked in Figure 4(a)-4(c) which is 1.9, 2, and 3.24 % lower compared to base diesel. It has also been observed that D70B20E10 blend shows maximum BSEC at all braking power. This can be explained that if biodiesel percentage increased the viscosity of blend increases, due to which more fuel has to be injected into the cylinder [26]. Also, low density and low heating value of ethanol enhanced the faster burning rate of blended fuel that increased BSEC to produce the same brake power [27]. At low brake power, BSEC increases due to the low heating value of ethanol. However, with an increase in load, combustion efficiency has been improved and for that BSEC decreases [8].



(a) 0.68 kW



(b) 2.05 kW



(c) 3.42 kW

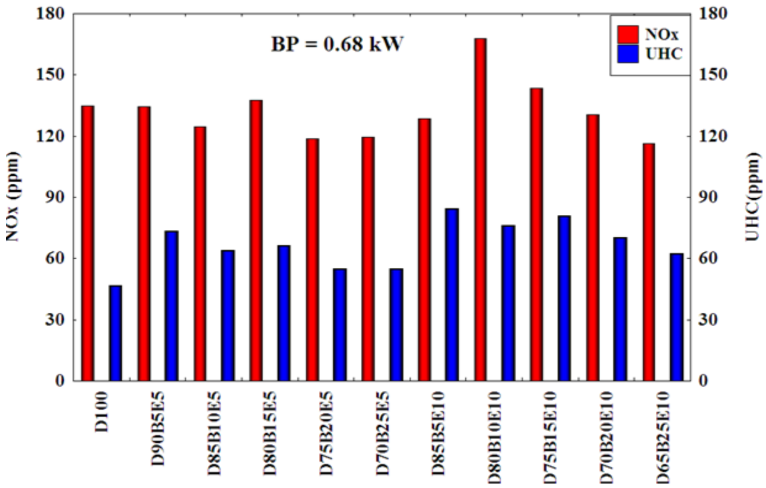
Figures 4. BSEC at different brake power.

Nitrogen Oxides Emission

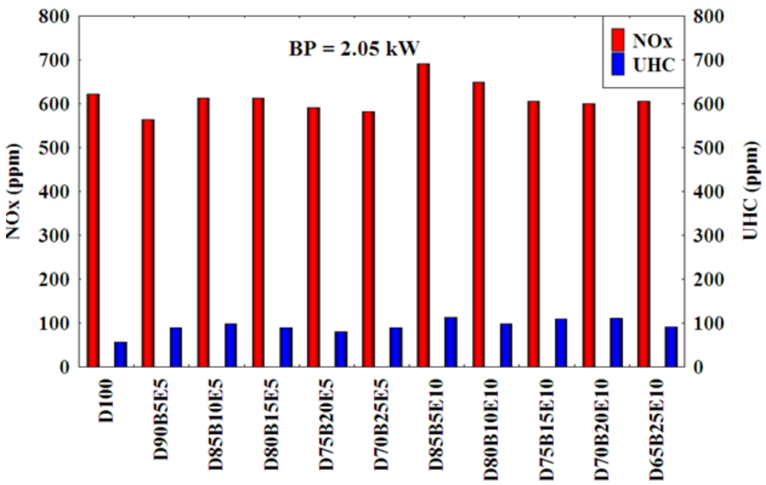
The variation of NOx at different brake power is illustrated in Figures 5(a)-(c) for different blends and diesel. The results show that the NOx emission for all blends is almost similar to diesel and increase in a linear fashion with an increase in brake power. A maximum reduction in NOx emission of 13.7, 9.17, and 4.7 % are observed at 0.68, 2.05, and 3.42 kW brake power for D90B5E5, D75B20E5, and D70B20E10 blend respectively. At higher brake power, the increase in NOx emission is caused due to high-temperature generation during the combustion. Maximum NOx emission for medium and high BP has been found for E10B5D85 blend. Because of low heat generation at low load, there is no such change in NOx emission for all test fuels. At medium to high load, NOx emission increases due to oxygen content in both biodiesel and ethanol that enhances the high combustion temperature. However, the relative increase in NOx emission is comparatively low at high load due to the better oxidation of nitrogen during combustion. Ignition delay has increased due to lower cetane value of ethanol which further increases the premixed combustion duration and premixed combustion temperature. It has also been noticed that with the increase in ethanol fraction from 5 to 10%, NOx emission increases more at medium to high load.

Unburnt Hydrocarbon Emission

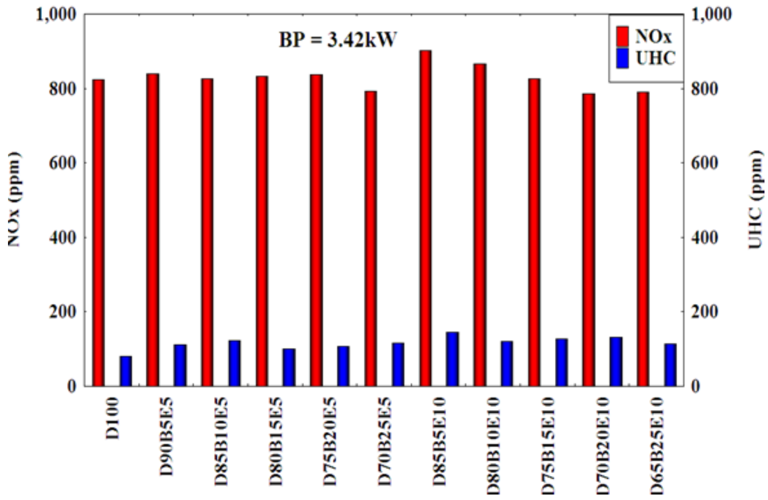
Partial combustion of fuel inside the combustion chamber is the main cause of the unburnt hydrocarbon emission. The variations of UHC emission with brake power for the diesel-palm biodiesel-ethanol ternary blend are compared in Figures 5(a)-5(c). It is found that among all ternary blend D70B20E5 shows lowest UHC emission. It has been observed that as brake power increases UHC emission increases for all test fuel, however for diesel it is lower compared to all other blends. An increase in 17, 42.9 and 24% UHC emission have been observed for D70B25E5, D75B20E5, and D80B15E5 respectively which is lowest compared to other blends. It is because of the incomplete combustion of the blends which is mainly due to the lower cetane number of ethanol [13]. It is also observed that as ethanol addition increases from 5 to 10%, the tendency of UHC emission also increases.



(a) 0.68 kW



(b) 2.05 kW



(c) 3.42 kW

Figures 5. Variation of NOx and UHC emissions at different brake power.

Trade-Off Study

Parallel success to the performance improvement and emissions reduction in a diesel engine is always a challenging situation. In reduction to a particular emission may lead to an increase in other emissions. In such circumstances, trade-off study between performance and emission parameters may lower the difficulties during the decision making. In this study, performance-emission trade-off between NOx-BSEC-BTE and NOx-UHC-BTE have been carried out to identify optimum ternary blend for maximum possible BTE and minimum emissions. From Figure 6(a), at 0.68 kW brake power, with the increase in biodiesel fraction and 5% ethanol, NOx emission decreases. As ethanol increases from 5 to 10 %, NOx emission again decreases with the increase of biodiesel addition with some penalty to BTE. The trend of increase in BTE has been observed at Zone A for blend D70B25E5 with some increase in NOx emission.

It has been noticed from trade-off at 2.05 kW (in Figure 6(b)) that BTE decreases for 10% ethanol fraction as compared to 5% ethanol. Among all blend, D85B5E10 and D75B20E5 exhibit more NOx emission which has shifted trade-off zone towards Zone B. As compared to D100, operation with D70B25E5 and D90B5E5 decrease both BSEC and NOx emission with no such change in BTE. From the trade-off, at 2.05 kW it has been observed that 5% ethanol fraction is much better to reduce BSEC and NOx emission with aid in higher BTE. From performance-emission tradeoff in Figure 6(c) at 3.42 kW brake power, it can be easily explained that contribution of 5% ethanol fraction is more effective to reduce BSEC with significantly higher BTE compared to 10% ethanol addition. Among all blend, D85B5E10 blend operation introduces more NOx emission which is shown in Zone C.

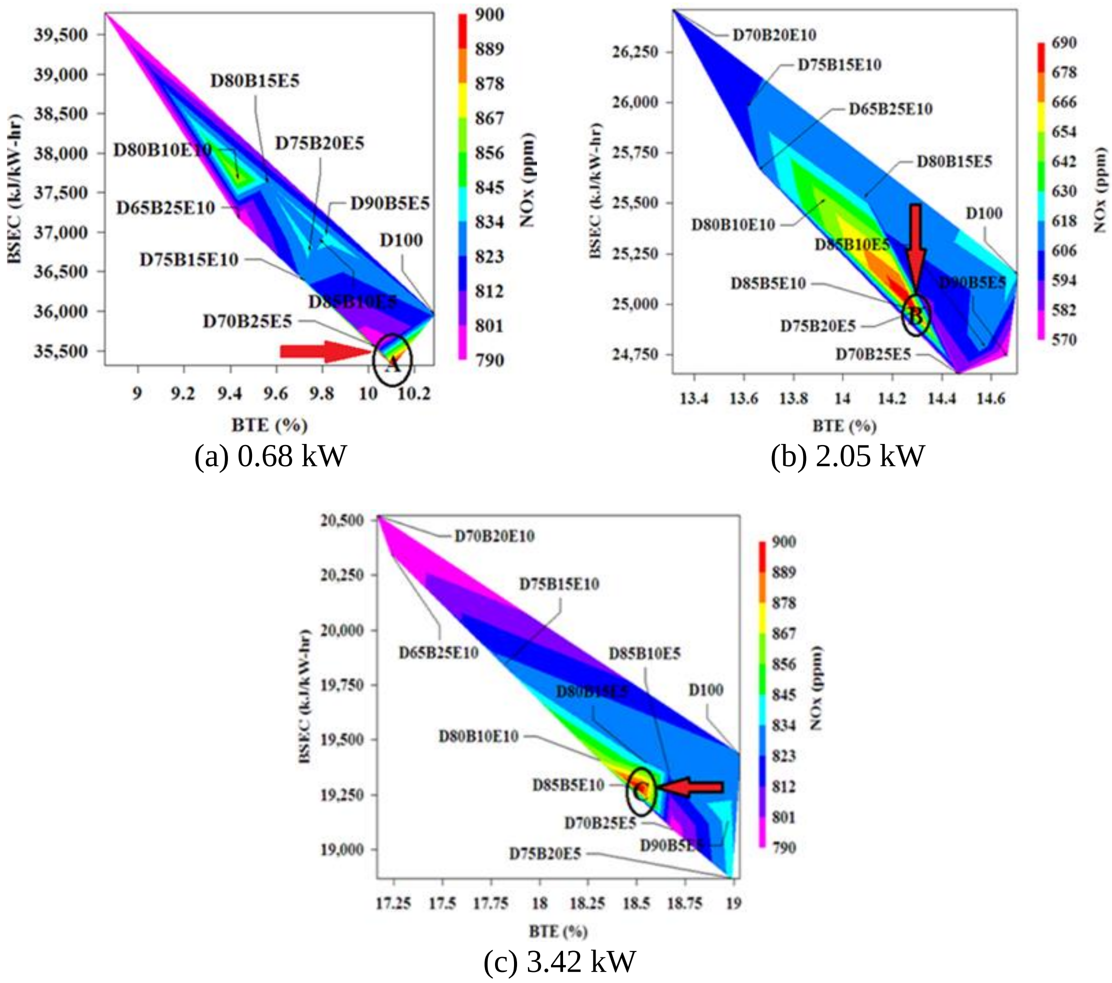
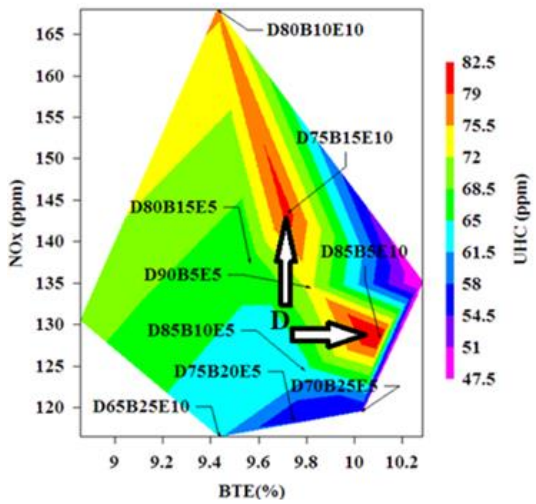
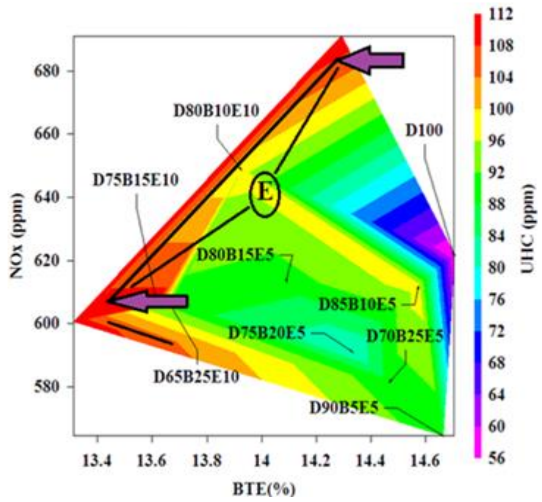


Figure 6. NOx-BSEC-BTE trade-off at different brake power.

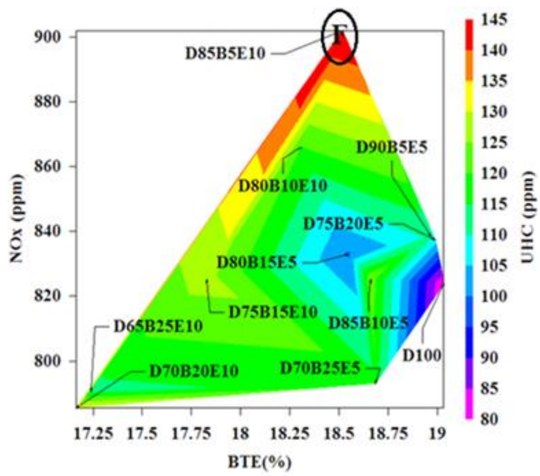
In Figure 7(a)-7(c) the trade-off study of NOx-UHC-BTE at three different brake power has been shown. It can be easily explained that ternary blend with 10% ethanol fraction is more prone in formation of NOx and UHC emissions which is shown in Zone D. Similar type of comprehensive idea have been illustrated by Majumder et al. [28] for performance-emission trade-off at a time. It has been clearly noticed from Figure 7(a) that D70B25E5 performs better in the highest reduction in UHC emission whereas D80B10E10 shows maximum NOx emission. At 2.05 kW brake power with 5% ethanol share, BTE increases with lower NOx emissions. There is no such improvement in UHC emission except D100, where 10% ethanol share represent maximum UHC emission which shifted trade-off in Zone E. From Figure 7(b), it has been observed that ternary blend with 5% ethanol share performs at higher BTE compared to 10% ethanol fraction. Such inherent challenges of performance-emission dilemma have been greatly reinforced and amplified by Banerjee et al. [29] for the new diesel engine operational paradigms. At 3.42 kW brake power, the maximum penalty in NOx and UHC emissions have been found for D85B5E10 blend is shown in Zone F (in Figure 7(c)).



(a) 0.68 kW



(b) 2.05 kW



(c) 3.42 kW

Figure 7. NOx-UHC-BTE trade-off at different brake power.

CONCLUSION

In this present study, the experiments have been performed to establish alternative use of the diesel-palm biodiesel-ethanol blend to achieve best ternary blend for engine performance and emissions. Based on the experimental results and trade-off analysis, conclusions are summarised below:

i. As compared to diesel some of the ternary blends have shown higher BTE at different brake power.
ii. As ethanol fraction increases from 5 to 10%, BTE decreases due to low cetane number of the blends.
iii. The highest increase in BTE are found 2.33, 1.8, and 2.4 % for D85B5E10, D90B5E5 and D75B20E5 respectively as compared to diesel.
iv. The maximum decrease in BSEC are found 1.9, 2, and 3.24 % for D85B5E10, D90B5E5 and D75B20E5 respectively as compared to diesel.
v. At medium to high load NOx emission increases due to high-temperature generation. Most of the ternary blend shows higher UHC emission which also increases with an increase in brake power.

vi. As compared to diesel, maximum NOx reduction of 13.7, 9.17, and 4.7 % and minimum UHC increase of 17, 42.9 and 24 % have been observed at 0.68, 2.05, and 3.42 kW respectively.
vii. Performance-emission trade-off reveals the effective participation of diesel-palm biodiesel-ethanol blends among which D70B25E5 is the optimal blend which enhanced the BTE with maximum reduction in UHC and NOx emissions. It has also been observed from trade-off that most of the ternary blend with 5% ethanol addition performs at lower BSEC rate.

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