iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 **Issue:** I **Month of publication:** January 2018

DOI: http://doi.org/10.22214/ijraset.2018.1356

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
Volume 6 Issue I, January 2018- Available at www.ijraset.com

Mathematical Correlation of Different Emission Characteristics Analysis of DI-Diesel Engine Fueled with lignocellulosic Biomass Derived N-butanol/diesel Blend using Response Surface Methodology

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Abstract: Utilization of renewable alcohols as fuel grabbed the attention of the researchers as they can be extracted from lignocellulosic bio-mass. In the present work the influence of EGR rate and injection timing on the performance and emission characteristics of a single cylinder, four stroke, direct injection diesel engine has been experimentally investigated using D70B30 (70% diesel and 30% butanol) blend as fuel. To conduct this study, we recorded the combustion and emission characteristics under nine operating conditions at three EGR rates (i.e. 10%, 20% and 30%) and three injection timings (i.e. 21°CA bTDC, 23°CA bTDC and 25°CA bTDC) under peak load at 5.3 bmep. Results indicate that at same EGR rate and injection timing D70B30 blend show 15% and 20% reduction in NO_x and smoke density respectively. When the EGR rate is increased there is a significant reduction in NOx emission with heavy penalty in smoke emission. Advancing the injection timing reduced the smoke emission by 60% and 22% increase in NOx concentration also gave better combustion behavior due to prolonged ignition delay. The statistical analysis is significant and engine running with n-butanol/diesel blend under 21°bTDC and 30% EGR had shown positive emission reduction. At 21°bTDC and 30% engine undergoes Low Temperature Combustion (LTC). It may be concluded that n-butanol can be an excellent substitute for fossil diesel and long term durability tests have to be carried out for its commercial usage in the conventional diesel engines.
Keywords: n-butanol, emission, Injection Timing, Exhaust Gas Recirculation, Response Surface Methodology

ABBREVATIONS

B(A)TDC	-	Before (After) Top Dead Centre
HRR	-	Heat Release Rate
CAS	-	Chemical Abstract Service
CO	-	Carbon monoxide
DI	-	Direct Injection
ULSD	-	Ultra low sulfur diesel
BTE	-	Brake Thermal Efficiency
D70B30	-	70% Diesel + 30% n-butanol blend by vol.
HC	-	Hydrocarbons
NO_x	-	Nitrogen Oxides
EGR	-	Exhaust gas recirculation

I. INTRODUCTION

The continuous use of fossil fuels as the major energy source has led the world to a potential energy and environmental crisis. This is due to the depletion of this energy source and consequent increase of exhaust gas emissions that accumulate in the atmosphere and bring about global warming also stringent emission regulations are driving the scientific community to find alternative renewable biofuels for use in diesel engines. In India, health cost due air pollution has been estimated around 3 per cent of its GDP and increasing automobile population will increase its share in the future. The outdoor air pollution from automobile is one of the major contributors to bring down the ambient air quality which badly affects both environment and human health, especially young children due to the immaturity of their respiratory systems. Ageing of vehicle add most environmental issues; hence it is essential to enhance the technological parameters by introducing new technologies, implementation of periodic inspection with maintenance and introducing cleaner fuels which may reduce exhaust emission concentration. To avoid the problems associated to fossil fuels, it becomes necessary to use cleaner and renewable energy sources. However, these new energy sources should compete with the prices of fossil fuels. In the last decades, several efforts have been conducted to produce chemical compounds that can replace fossil fuels using microorganisms. For that, these compounds, normally corresponding to higher alcohols or long-chain fatty acids, must have properties comparable to those of current transportation fuels. However, native organisms cannot synthesize these fuels in a cost-effective way. Owing to that, advances in metabolic engineering, as well as in synthetic and systems biology, appear as a viable alternative for the production of these compounds. This review shows the recent developments in metabolic engineering of Escherichia coli for higher alcohols production and tolerance, emphasizing two different pathways: (i) the fermentative pathway, originally from microorganisms from the genera Clostridia; and (ii) the non-fermentative pathway, also known as the keto acid pathway. Engineering these synthetic pathways in heterologous organisms that are well-known and better suited for large-scale growth and industrial production, normally E. coli and Saccharomyces cerevisiae, can significantly improve advanced biofuels production. The most convenient and cost-effective approach for large-scale production of advanced biofuels may be the engineering of microorganisms. First, recent advances in molecular, systems, and synthetic biology now allow for the rapid engineering of microbial biosynthetic pathways to produce a variety of advanced biofuel candidates such as alcohols, esters, alkanes, and alkenes from the isoprenoid and fatty acid pathways. Second, industrial fermentation knowledge can be readily applied to the microbial production of advanced biofuels. Third, as microbial advanced biofuels would be produced in bioreactors, production facilities could be placed wherever needed. Finally, once the breakdown of lignocellulosic biomass is economically feasible, the microbes could generate biofuel not from starchy agricultural products but rather from lignocellulosic biomass that cannot be used for food. In the last 2 years, production of many potential advanced biofuels has been reported. Clostridia have evolved and developed exceptional substrate diversity and are capable of using a variety of materials especially lignocellulose and C1 gases. Cellulolytic clostridia are able to directly use lignocelluloses, the most abundant biomass on earth, thus, they have been widely studied for the production of alcohols through consolidated bio processing (CBP), a possible ultimate solution for the economical utilization of lignocellulosic biomass. Energy has became hot topic of the current world, utilizing the non-renewable energy resources like petroleum products have forced the mankind to move to renewable energy research in order to meet the escalating energy demand and also high exhaust emissions from fossil fuel is an important reason. Researchers have shown their interest on the domain of engine or fuel related techniques to meet the emission legislation. Past decade has witnessed advanced engine related techniques like variable valve timing, exhaust gas recirculation, diesel particulate filter, catalytic converter etc., likewise there have been many inventions on fuel related techniques those include alternative fuels like biofuel, oxygenated fuels, first generation alcohols, second generation alcohols etc. Butanol is deemed as one of the next generation biofuels for transportation and combustion engine applications which is a 4-carbon straight chain alcohol that can be produced from biomass (bio-butanol) as well as fossil fuels (petro-butanol). Nevertheless both have same chemical properties and produce similar effects when used in engines, hence it could be considered as a good alternative fuel for diesel engines and it provides several advantages over the lower alcohols like methanol and ethanol, such as higher energy density, higher cetane number, higher heating value, better miscibility, and blend stability with diesel fuel. Low cetane number property of n-butanol prevents its direct usage in an unmodified compression ignition engine. Diesel/butanol blends are one of the several possibilities that can be utilized to make diesel technology compatible with alcohols, as a consequence of its lower polarity exhibits better miscibility characteristics with diesel unlike lower or short chain alcohols. However when blended with diesel, butanol lowers the cetane number of the blends which brings about deterioration of auto- ignition characteristics and a longer ignition delay, also it is worth to note that cetane number cannot provide a reasonable indication of ignition delay. In other words, it is necessary to pay attention on the effect of n-pentanol on spray ignition from both physical mixing and chemical reaction aspects. [1] studied the basic effects of ageing and technological substitution of motor vehicles on their air emissions. This model studies, number of effects such as fleet renewal rate, new technology penetration in the vehicle market, emission deterioration with age, and importance of additional technological measures that affect both new and in-use vehicle, through the introduction of improved fuel in the market. With this approach authors developed a mathematical model, provided sufficient experimental data and statistical data, it is possible to assess the environmental impact of large number of technical and non technical measures aiming to control the emission from the motor vehicle. [2] investigated the case study of Sweden for cost-efficient use of biofuels in road transport under system-wide CO2 reduction targets to 2050, and the effects of implementation of targets for an almost fossil-free road transport sector to 2030. This study prospects for first and second generation biofuels, but also electricity is included in the analysis as an alternative option to biofuels. The results of the study show that biofuels in the road transport sector can make an important contribution to the achievement of stringent CO2 emission reductions and fossil fuel phase-out targets without considerable system cost increases or excessive reliance on biofuels imports. [3] numerically investigated the effect of injection timing on performance and emission characteristics of a CI engine fuelled with diesel and methyl soyate and make a comparison between the two. The simulations have been carried out for three different injection timings of 17°, 20°and 23° bTDC. It has been observed that there is a decrease in the brake thermal efficiency and an increase in the brake specific fuel consumption with the advancement in injection timing for both the fuels, the performance of diesel being better than the biodiesel. Exhaust gas temperature increases along with the NOx and CO2 emissions, while the particulate matter and smoke emissions decrease with the advancement in injection timing. NOx, CO2 emissions and exhaust temperature are found to be more, while PM and smoke emissions are less for methyl soyate when compared to diesel. [4] reviewed the effects of alternative fuels on the combustion characteristics and emission products from diesel engines, it has been observed from several papers that there is significant reduction of regular gas and PM emissions by the use of alcohol/diesel dual fuel, while unregulated emissions such as methanol, ethanol, acetaldehyde, formaldehyde, ketone, have increased compared to those from diesel fuel. [5] investigated low temperature combustion and emission characteristics of four different fuels at different EGR ratios. Pure diesel (D100), a diesel and gasoline blend with a volume ratio of 70:30 (D70G30), a diesel and n-butanol blend with a volume ratio of 70:30 (D70B30) and a blend of diesel, gasoline and n-butanol with a volume ratio of 70:15:15 (D70G15B15). When the EGR ratio was greater than 25%, the emissions of soot, CO and THC increased rapidly with the rising EGR ratio due to the decrease in excess air coefficient and to the excessively long ignition delay period. The emissions of soot, NOx, CO and THC and the number concentration of particles reached their optimum values during the combustion of D70B30 at an EGR ratio of approximately 25%. [6] in this work studied the effects of blending n-pentanol, a second generation biofuel with diesel on the performance and emission characteristics of a diesel engine under exhaust gas recirculation (EGR) conditions are investigated. Tests were performed on a single-cylinder, constant-speed, un-modified, direct-injection diesel engine using four n-pentanol/diesel blends: 10%, 20%, 30% and 45% (by volume). The possibility of using a high pentanol/diesel blend (45%) was also explored with an objective to maximize the renewable fraction in the fuel. Three EGR rates (10%, 20% and 30%) were utilized with an intention to reduce the high nitrogen oxides (NOx) that were prevalent at high engine loads using these blends. It was found that simultaneous reduction of NOx and smoke emissions can be achieved using the combination of pentanol/diesel blends and a medium EGR rate (20–30%) with a small drop in performance. Lignocellulosic biomass derived n-butanol application as a bio-alcohol additive to diesel as blend could be an advantageous strategy to improve the utilization of a renewable bio-component (n-butanol). Therefore, the present study attempts to substitute 30% by vol. of fossil diesel (D) with n-butanol 30% by vol. by formulating D70B30 blend in mixing ratio by volume. The effect of this n-butanol addition to diesel on different emissions characteristics of a DI diesel under the influence of EGR and injection timing was studied by developing a statistical model using response surface methodology.

II. MATERIALS AND METHODS

A. Test fuels

Table 1 shows the main properties of diesel, n-butanol and test blend for this study. The ultra-low sulfur diesel was procured from Bharath Petroleum; Chennai with a cetane number of 54 is used as the baseline fuel. From baseline tests, it has been observed that neat diesel produces high NOx and smoke emissions due to lack of oxygen during the combustion process. Hence in order to enhance the combustion process high oxygenated n-butanol(CAS NO: 71-36-3) certified to the purity of 98% was used as an additive which was procured from Merck Millipore. D70B30 (70% diesel, 30% butanol) were prepared at the mixing ratio of volume. Mixing lower volatility n-butanol to higher volatility diesel could promote the evaporation of the blend.

Table 1 Properties of test fuels

Properties	Test method	ULSD	n-butanol	D70B30
LHV (MJ/kg)	ASTM D240	41.82	34	39.474
ν at 30°C (mm^2/s)	ASTM D445	3.80	2.2	3.334
ρ (kg/m3)	ASTM D4052	838	810	829.6

Cetane number	ASTM D4737	54	-	-
Flash point (°C)	ASTM D93	70	36	59.8

LHV – low heating value; ν – kinematic viscosity; ρ – density; CCI – calculated cetane index; B – n-butanol; ULSD-diesel

B. Test engine and facilities

Tests were carried out in a single cylinder, 4 stroke, water-cooled, direct injection diesel engine whose layout is in Fig.1.

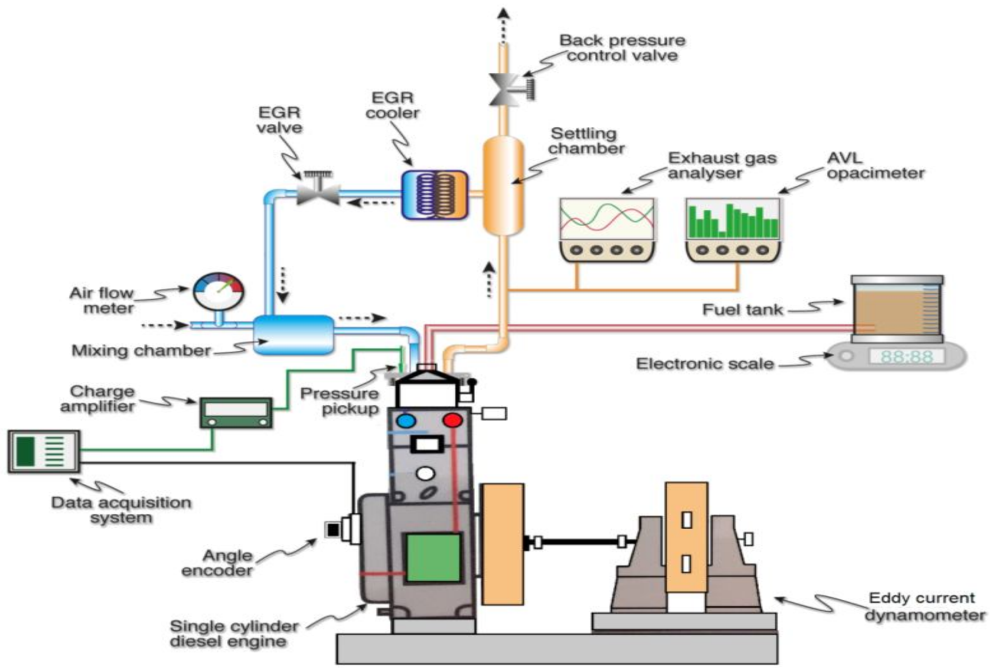

Fig.1 Layout of the experimental setup[7]

The specifications of the engine are presented in Table 2.

Table 2 Engine specifications

Make and model	Kirloskar, TV1 make, 4-Stroke Diesel
Number of cylinders	One
Combustion chamber	Hemispherical open type
Cooling system	Water-cooled
Lubricating oil	SAE40
Piston	Shallow Bowl-in type
Bore, mm	87.5
Stroke, mm	110
Connecting rod length, mm	238
Swept volume, cm3	661
Clearance volume, cm3	38.35
Compression ratio	17.5:1
Rated power, Kw	5.2
Rated speed, rpm	1500
Injection type	Direct Injection
Fuel injection pump	MICO inline, with mechanical governor
Injection pressure, bar	210
Number of Nozzle holes	3

Spray-hole diameter, mm	0.25
Spray cone angle, °	110
Needle lift, mm	0.25
Valve diameter, mm	34.2
Maximum valve lift, mm	10.1

The instrumentation facility attached to the engine for measuring critical parameters is briefly listed in Table 3. The range, accuracy and uncertainties of the instruments were given in Table 4.

Table 3 Details of the Engine Instrumentation

#	Instrument	Make and Model
1	Dynamometer	Technomech, TMEC-10, Eddy current type, 7.5kW, 1500-6000rpm. Water-cooled.
2	Dynamometer loading unit	Apex, AX-155, Constant speed type
3	Load sensor	SensotronicsSanmar6000, Load cell, Strain gauge type , S beam, Capacity 0-50 kg
4	Pressure transducer	PCB Piezotronics, HSM111A22, Range 5000 psi. with low noise cable
5	Data acquisition system	National Instruments - USB-6210 Bus Powered M Series. 16-bit, 250kS/s, Piezo powering unit Model AX-409.
6	Crank angle encoder	Kubler-Germany 8.3700.1321.0360, Dia: 37mm. Crank angle sensor - Speed 5500RPM with TDC pulse
7	Fuel flow transmitter	Yokogawa, EJA110-EMS-5A-92NN, Calibration range 0-500 mm of H2O
8	Air flow transmitter	Pressure transmitter, Range 0- 250 mm of H2O
9	Resistant temperature detector	PT100 – Range 0 to 100°C
10	Thermocouple	Type K - Range 0 to 1200°C, O/P 4–20mA
11	Gas analyser (NO, CO and HC)	AVL 444N
12	Smoke meter	AVL 437C

Table 4 Range, accuracy and percentage uncertainties of instruments

Instrument	Measured Quantity	Range	Accuracy	Uncertainties, %
Gas analyzer	NOx	0 - 5000 ppm	<500ppm: ±50 ppm	±5
	HC	0 - 20000 ppm	<200ppm: ±10ppm >200ppm: ±5%	±5
	CO	0 - 10%	<0.6% vol: ±0.03% >0.6% vol: ±5%	±5
Smoke meter	Smoke density	0 – 1000 mg/m^3	±0.1 mg/m^3	±1.0
Pressure pickup	Cylinder pressure	0 – 250bar	±0.1 bar	±0.1
Crank angle encoder	Crank angle	0 - 360°	±1°	±0.2

C. EGR setup

EGR method is an efficient method used for reduction of high NO_x emission from diesel engines. In this study cooled EGR technique is adopted owing to its advantages over hot EGR, usage of greater proportion of EGR is achieved as cooling increases the density of the re-circulated exhaust gas. The required quantity of exhaust gas is directed to the EGR cooler which acts as a heat exchanger, where cooling of hot exhaust gases is achieved by the surrounding cooling water which was maintained at a constant temperature. In this study, temperature drop in exhaust gas is achieved upto 36°C. EGR rate is controlled by an EGR valve. Orifice meter is used for measuring the flow rate of exhaust gas. Re-circulated exhaust gas and incoming air is mixed well in a mixing chamber before they inducted inside the combustion chamber. EGR quantity was determined using the relation,

$$EGR\% = \left[\frac{(CO_2)_{intake}}{(CO_2)_{exhaust}}\right] \times 100 \qquad (1)$$

The quantity of CO_2 in the exhaust was measured by the AVL 444N gas analyzer by adjusting the control valve to vary the flow rate of the exhaust until the quantity of CO_2 in the intake reaches the desired value. The similar method was used in author's previous work (De Poures et al. 2017[7], Rajesh kumar & Saravanan 2015[6]) to determine the EGR rates.

D. Error Analysis

The errors associated with various measurements and calculations of parameters are computed in this section. The maximum possible errors in calculations were estimated using the method proposed by Moffat [8]. Errors were estimated for minimum values of the output and accuracy of the instrument. If an estimated quantity S, depends on independent variables like (x_1, x_2, x_3… x_n), then the error in the values of S is calculated by using the equation,

$$\frac{\partial S}{S} = \left\{\left(\frac{\partial X_1}{X_1}\right)^2 + \left(\frac{\partial X_2}{X_2}\right)^2 + \cdots + \left(\frac{\partial X_n}{X_n}\right)^2\right\}^{\frac{1}{2}} \qquad (2)$$

Where$\left(\frac{\partial X_1}{X_1}\right)$, $\left(\frac{\partial X_2}{X_2}\right)$ etc, are the errors in the independent variables. $\partial X_1$is the accuracy of the measuring instrument and X_1 is the minimum value of the output measured during the experiment.

Since brake thermal efficiency (BTE) is calculated from fuel consumption, errors associated with it can be represented by equation (3) as follows,

$$\left(\frac{\partial BTE}{BSFC}\right) = \left\{\left(\frac{\partial Torque}{Torque}\right)^2 + \left(\frac{\partial rpm}{rpm}\right)^2 + \left(\frac{\partial time}{time}\right)^2\right\}^{\frac{1}{2}} \qquad (3)$$

As per equation (3), the maximum possible error in the calculation of BTE and BSFC was determined to be 0.33%. Similarly, the errors associated with the measurements of temperature, cylinder pressure and the crank angle was determined to be 0.5%, 1.35% and 2% respectively. This method of error analysis was adopted in author's previous study (Rajesh Kumar &Saravanan 2016b).

E. Test procedure

Experiments were performed under steady-state condition and at peak load, which corresponds to a brake mean effective pressure of 5.3 bar. Combustion and emission characteristics of the test engine were recorded at nine operating conditions by progressively increasing the three cold EGR rates (i.e. 10%, 20% and 30%) and three injection timings (i.e. 21°CA bTDC, 23°CA bTDC and 25°CA b TDC), whereas injection pressure is held constant at 21 Mpa. The fuel blend ratio was designated as W70P30 and was kept in observation for 90 days before conducting this study to ensure that there is no phase separation. The tests were conducted on the same day and almost at same environmental conditions, repeatability of the experimental observations is ensured by averaging the results which is repeated of two times. The baseline tests were conducted with neat diesel and waste plastic oil at same operating conditions as stated above. The injection timing was advanced or retarded by 2°CA bTDC by adding or removing the shim respectively which is located in between the engine and fuel pump. The EGR rate and injection timing were varied for each trial and the recordings were made.

III. EXPERIMENTAL STRATEGY

A. Response Surface Design

Response surface method (RSM) was employed to investigate the emission characteristics of a specified fuel blends in a diesel engine. It quantifies the relationships between one or more measured responses and the vital input factors. The objective of the RSM is to find a desirable location in the design space. This could be a maximum, a minimum or an area where the response is stable over a range of the factors. Goals might include meeting a set of specifications for several responses simultaneously. The first step in creating a response surface design is to select an appropriate model that suits the application. Using the selected model, the required number of input factor combinations will be generated.

1). Central Composite Design: CCD as a popular response surface design was employed to fit the response model. In this model two factors, namely, injection timing and exhaust gas recirculation (EGR) was considered along with various output responses as shown in Table 5.The model was generated using two factors and three levels model. In general the CCD is a rotatable design that can be used with five levels. In this study, a face centered model was employed such that the investigation was carried out within the specified range of factors as three level model.

Basically, the CCD model has three groups of design points, namely, fractional factorial design points, axial or star points and center points. The two-level factorial part of the design consists of all possible combinations of the +1 and -1 levels of the factors as shown in Figure 1. For the two factor case there are four design points i.e., (-1, -1), (+1, -1), (-1, +1), (+1, +1). The star points have all of the factors set to 0, the midpoint, except one factor, which has the value +/- Alpha (α).

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
Volume 6 Issue I, January 2018- Available at www.ijraset.com

Table5. Experimental parameters

S. No	Factors	Units
1	Injection timing	Degree
2	Exhaust gas recirculation	%
	Responses	
1	CO	ppm
2	HC	ppm
3	CO_2	% vol.
4	NO_x	ppm
5	Air fuel equivalence ratio (λ)	-
6	Smoke	FSN
7	Smoke density	mg/m^3
8	Smoke opacity	%

For a two factor problem, the star points are:(-Alpha, 0), (+Alpha, 0), (0, -Alpha), (0, +Alpha). The value for Alpha is calculated in each design for both rotatability and orthogonality of blocks. The default value is set to the rotatable value. Another position the star point is at the face of the cube portion on the design. This is commonly referred to as a face-centered central composite design which was employed in this investigation. It was created by setting the alpha value equal to one, or choosing the Face Centered option. This design only requires three levels for each factor.

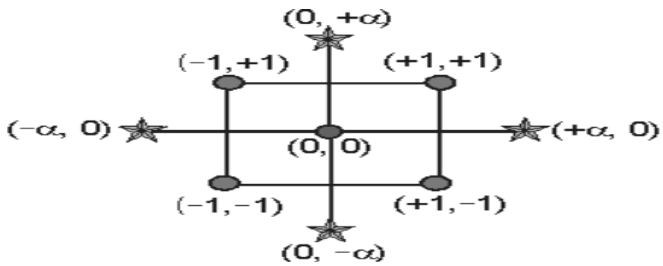

Fig.2. Design points of CCD

Table 6.Design matrix

	Factor 1	Factor 2
Run	A: TIME	B: EGR
1	23	30
2	21	30
3	25	20
4	25	30
5	21	20
6	23	20
7	25	10
8	23	10
9	23	20
10	23	20
11	23	20
12	23	20
13	21	10

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
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Based on these considerations, the design matrix for this investigation was generated as shown in Table 6. The developed design involved a total of 13 experiments including a three level two factor design. The experiments were conducted in based on the run order as given in Table 6, to ensure, no uncontrolled variables contribute to the repeatability and do not affect the results. The analysis by CCD involved estimation of the coefficients in the polynomial response model developed using a nonlinear regression method. Considering all the linear, square, and interaction terms, a quadratic response model can be expressed as

$$= \;_0 + \sum \qquad + \sum \qquad ^2 + \sum \qquad + \qquad (4)$$

Where, y is the predicted response, x_i ,x_j are the coded values of the independent process variables, and e is the residual error. Also, β_0, β_i, β_{ii} and β_{ij} are the constant, linear, quadratic, and interaction coefficients, respectively.

IV. RESULTS AND DISCUSSION

The emission characteristics of the fuel blend were investigated employing the CCD model. The analysis was carried out for various responses and the influence of injection timing and EGR on the emission characteristics of n-butanol/diesel blends was analyzed. The statistical analysis of the each response is discussed as follows,

A. *Accuracy Of Predicted Data*

The experiments were carried out and the measured responses were analyzed using the regression analysis. Figure 3, shows the predicted vs. actual plot for all the responses that was prepared using linear curve fit. It shows that the measured responses have adequate linearity that fit well on the curve and the deviations of results are very less in all the responses.

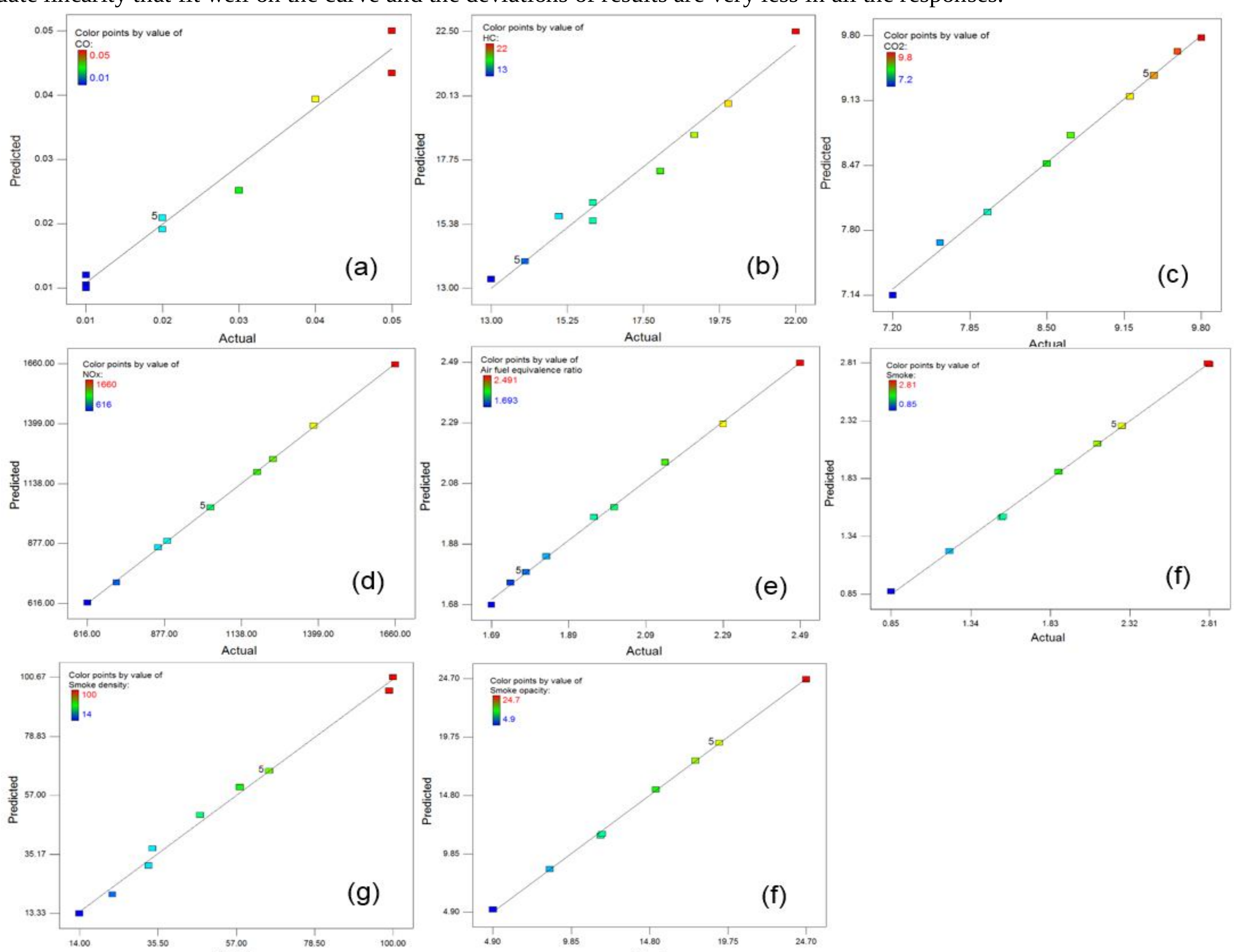

Figure 3. Predicted vs. actual plot

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B. Development of Mathematical Model

The modelling was started with a quadratic model including linear, squared and interaction terms. Significant terms in the model for the response were found by analysis of variance (ANOVA). Significance of factor was evaluated by the F-statistic calculated from the data. The experimental data was evaluated with various statistical analysis such as p value, F value, degrees of freedom (DF), sum of squares (SS), mean sum of squares (MSS), coefficient variation (CV), determination coefficient (R^2), adjusted determination of coefficient (R^2a), etc. and it reflects to the statistical significance of the mathematical model. The analysis of variance for the measured results was tested and the results are tabulated. The probability was checked with 5% failure criteria. It is considered that the main or interaction effect is significant if the probability is less than 5%. The ANOVA for each responses are discussed as follows,

1) *Analysis of CO emission:* The influence of CO emission on the input factors was analyzed using experimental measurements. It was tested with a quadratic polynomial model and the significant terms of CO emission can be identified from the ANOVA Table 7.The Model F-value of 57.24 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicates that the model terms are significant. In this case A, B, $B^2$are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Table 7. ANOVA for CO emission

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	
Model	0.002268	5	0.000454	57.24265	< 0.0001	significant
A-TIME	6.67E-05	1	6.67E-05	8.414508	0.0230	
B-EGR	0.002017	1	0.002017	254.5389	< 0.0001	
AB	0.000025	1	0.000025	3.15544	0.1189	
A^2	5.25E-06	1	5.25E-06	0.663212	0.4422	
B^2	0.000112	1	0.000112	14.18653	0.0070	

It was noticed that the "Pred R-Squared" of 0.8131 is in reasonable agreement with the "Adj R-Squared" of 0.9591. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case, the ratio of 22.946 indicates an adequate signal. Hence, this model can be used to navigate the design space. The quadratic mathematical correlation of input factors and the CO emission was developed as shown in Eq.(5).

$$CO = 0.021 – 3.333\times10^{-3}A+ 0.018\, B–2.500\times10^{-3}\, AB+1.379\times10^{-3}\, A^2 +6.379\times10^{-3}B^2 \qquad (5)$$

The main effect and interaction effects of CO emission on the input factor is plotted in Figure 4.(a and b).The plot shows the influence of response on injection time (A) and EGR (B) in its mean level. It is noticed that the CO emission is in decreasing trend as the factor A is varied from minimum to maximum level, whereas it is increasing as the factor B is varied within the specified range.

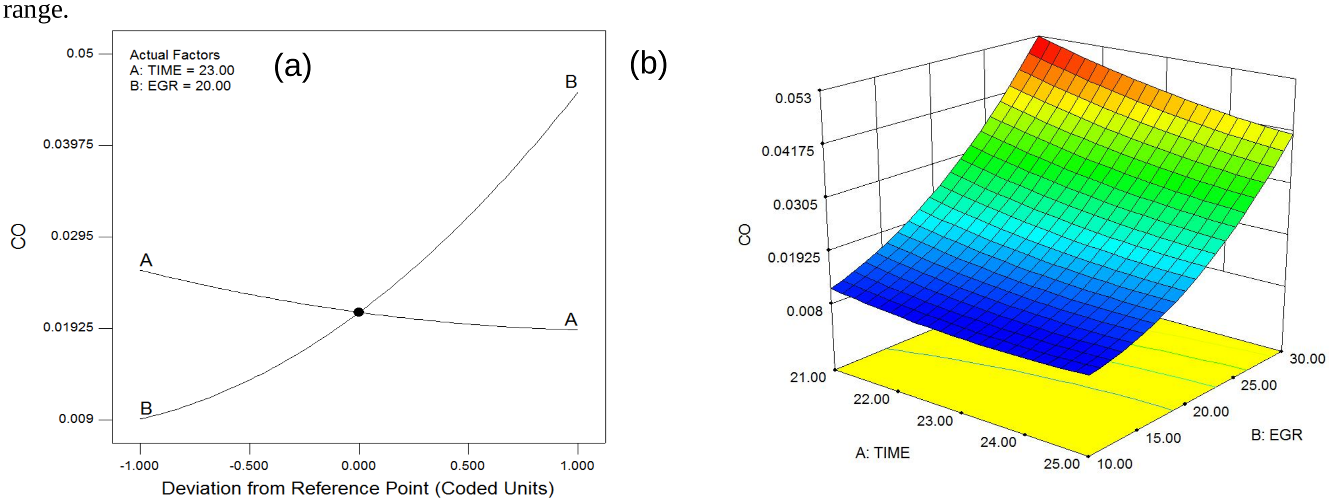

Figure 4.Response plot for CO, (a).Main effect, (b). Interaction effect

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It is noticed from the interaction plot that the CO emission has negligible change when the factor A is varied within the specified range when the factor B is in the lower level. But the factor is in decreasing trend as it was varied from minimum to maximum level when the factor B is at maximum.

2) *Analysis of HC emission:* The influence of HC emission on the input factors was analyzed using experimental measurements. It was tested with a quadratic polynomial model and the significant terms of CO emission can be identified from the ANOVA Table 8.The Model F-value of 78.34 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case A, B, A^2, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Table 8. ANOVA for HC emission

	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob> F	
Model	93.25641	5	18.65128	78.33538	< 0.0001	significant
A-TIME	4.166667	1	4.166667	17.5	0.0041	
B-EGR	42.66667	1	42.66667	179.2	< 0.0001	
AB	1	1	1	4.2	0.0796	
A^2	17.2619	1	17.2619	72.5	< 0.0001	
B^2	11.04762	1	11.04762	46.4	0.0003	

It is noticed that the "Pred R-Squared" of 0.8212 is in reasonable agreement with the "Adj R-Squared" of 0.9699. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case, the ratio of 27.652 indicates an adequate signal. This model can be used to navigate the design space. The quadratic mathematical correlation of input factors and the HC emission was developed as shown in Eq.(6).

$$HC = 14.00 + 0.83\,A + 2.67\,B + 0.50\,AB + 2.50\,A^2 + 2.00\,B^2 \quad (6)$$

The main effect and interaction effects of HC emission on the input factor is plotted in Figure 5.(a and b). The plot shows the influence of response on injection time (A) and EGR (B) in its mean level. It is noticed that the HC emission is in increasing trend when both the factors A and B is varied from minimum to maximum level. Also, it is observed that the factor A has a drop in the mean and increasing with higher level.

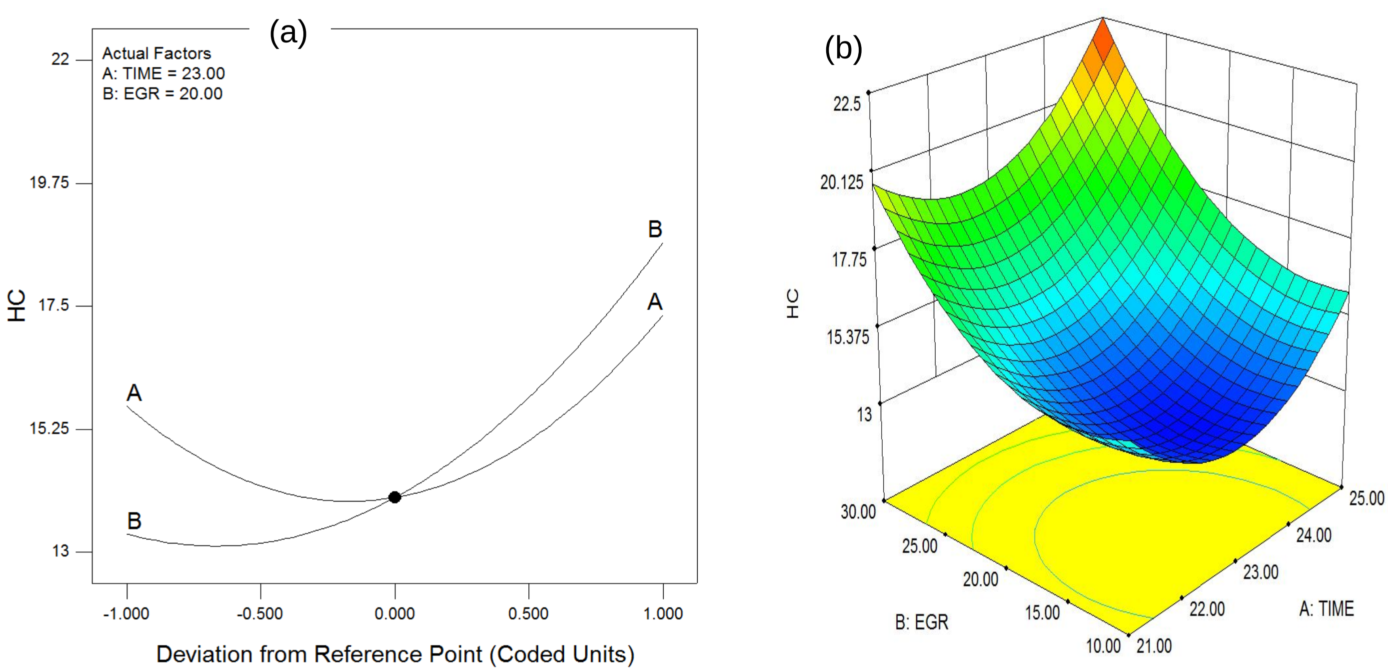

Figure 5.Response plot for HC, (a).Main effect, (b). Interaction effect

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It is noticed from the interaction plot that the HC emission has significant change as it was varied within the specified levels. The HC emission is higher when the EGR is at its maximum level. Also it was noticed that the HC emission has a drop when the EGR is in the maximum level and the factor is at its mean.

3) *Analysis of Co_2 Emission:* The influence of CO_2 emission on the input factors was analyzed using experimental measurements. It was tested with a quadratic polynomial model and the significant terms of CO_2 emission can be identified from the ANOVA Table 8. The Model F-value of 608.84 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case A, B, AB, A^2, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Table 8. ANOVA for CO_2 emission

	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob> F	
Model	8.210351	5	1.64207	608.8407	< 0.0001	significant
A-TIME	3.375	1	3.375	1251.37	< 0.0001	
B-EGR	1.5	1	1.5	556.1644	< 0.0001	
AB	0.0225	1	0.0225	8.342466	0.0234	
A^2	2.565525	1	2.565525	951.2359	< 0.0001	
B^2	0.035764	1	0.035764	13.26027	0.0083	

The "Pred R-Squared" of 0.9782 is in reasonable agreement with the "Adj R-Squared" of 0.9961. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case, the ratio of 74.792 indicates an adequate signal. This model can be used to navigate the design space. The quadratic mathematical correlation of input factors and the CO_2 emission was developed as shown in Eq.(7).

$$CO_2 = 9.39 + 0.75\,A + 0.50\,B + 0.075\,AB - 0.96\,A^2 - 0.11\,B^2 \quad (7)$$

The main effect and interaction effects of CO_2 emission on the input factor is plotted in Figure 6.(a and b). The plot shows the influence of response on injection time (A) and EGR (B) in its mean level. It is noticed that the CO_2 emission is rapidly increased till the factor A reaches its mean and then dropped gradually. But the CO_2 is in increasing trend as the factor B is varied with the specified level.

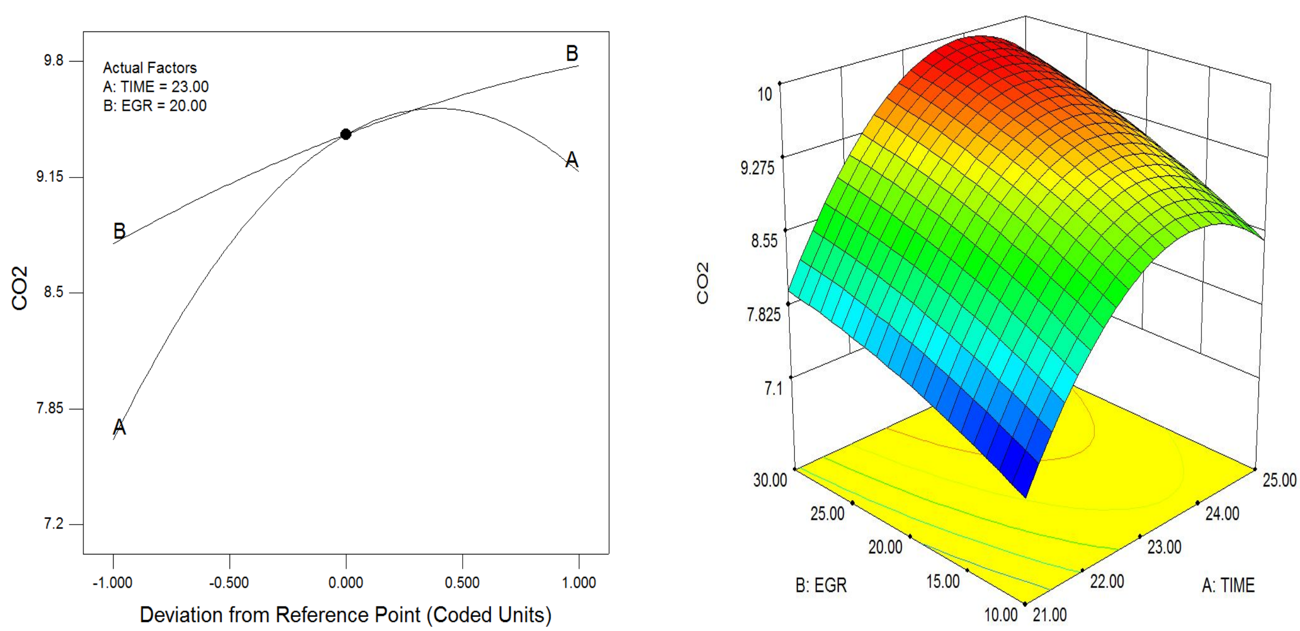

Figure 6.Response plot for CO_2, (a).Main effect, (b). Interaction effect

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
Volume 6 Issue I, January 2018- Available at www.ijraset.com

It is noticed from the interaction plot that the CO_2 is in increasing trend as the factor B is increased when the factor A is varied in its specified levels. Also, the CO_2 in increasing trend till the factor A reaches its mean and gradually dropped beyond mean value. It is noticed that the Co_2 emission is maximum when the factor A is in mean value at higher EGR levels.

4) *Analysis of NO_x emission:* The influence of NO_x emission on the input factors was analyzed using experimental measurements. It was tested with a quadratic polynomial model and the significant terms of NO_x emission can be identified from the ANOVA Table 9. The Model F-value of 8254.95 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicates that the model terms are significant. In this case A, B, AB, A^2, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Table 9. ANOVA for NO_x emission

	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob> F	
Model	907367	5	181473.4	8254.953	< 0.0001	significant
A-TIME	699733.5	1	699733.5	31829.83	< 0.0001	
B-EGR	189392.7	1	189392.7	8615.188	< 0.0001	
AB	12996	1	12996	591.1685	< 0.0001	
A^2	602.9959	1	602.9959	27.42938	0.0012	
B^2	2877.163	1	2877.163	130.8778	< 0.0001	

The "Pred R-Squared" of 0.9983 is in reasonable agreement with the "Adj R-Squared" of 0.9997. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case, the ratio of 325.975 indicates an adequate signal. This model can be used to navigate the design space. The quadratic mathematical correlation of input factors and the NO_x emission was developed as shown in Eq.(8).

$$NO_x = 1034.21 + 341.50\ A - 177.67\ B - 57.00\ AB + 14.78\ A^2 + 32.28\ B^2 \quad (8)$$

The main effect and interaction effects of NO_x emission on the input factor is plotted in Figure 7.(a and b). The plot shows the influence of response on injection time (A) and EGR (B) in its mean level. It is noticed that the NO_x is increasing as the factor A is varied from minimum to maximum level, whereas it is decreasing as the factor is varied from minimum to maximum level.

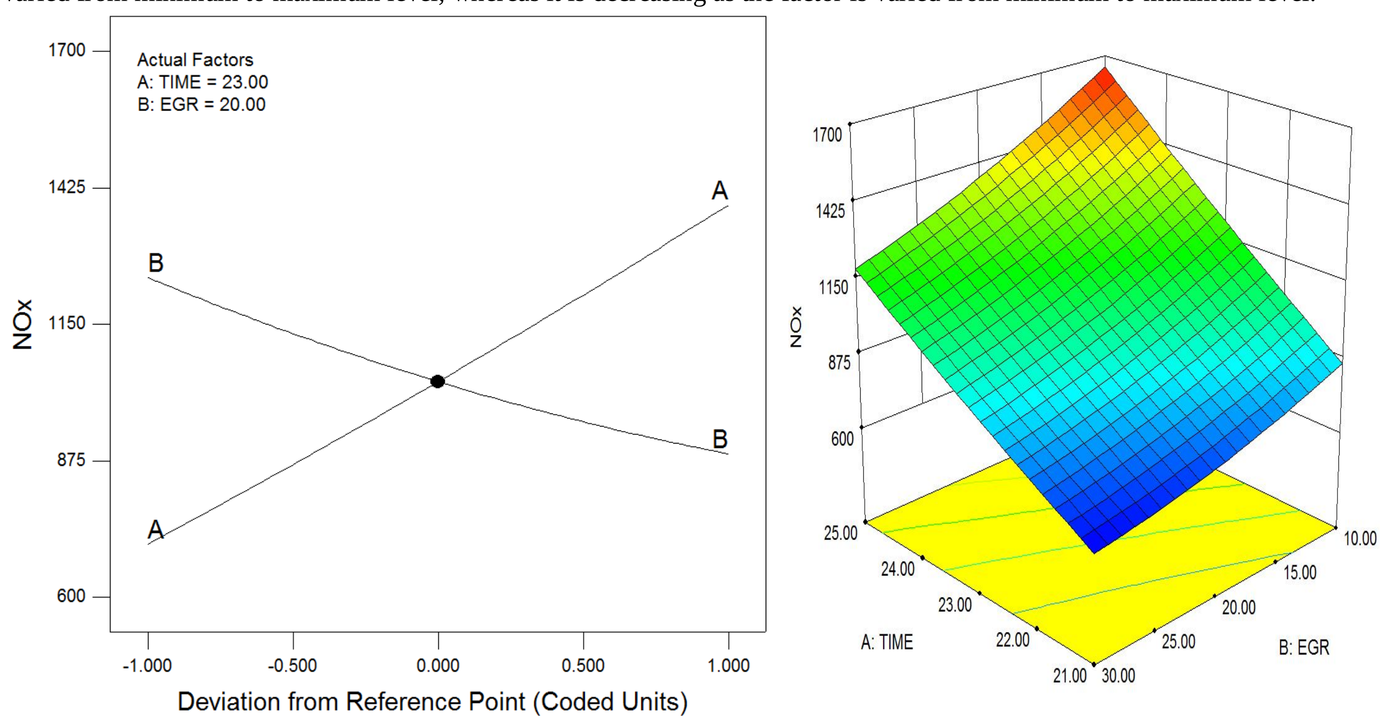

Figure 7.Response plot for NO_x, (a).Main effect, (b). Interaction effect

It is noticed from the interaction plot that the NOx is in decreasing trend as the factor B is increased when the factor A is varied in its specified levels. It is noticed that the NOx is increasing as the factor A is increased for all the levels of the factor B. The emission is higher when both the EGR and the injection time is high.

5) *Analysis of air fuel equivalence ratio (λ):* The influence of the air fuel equivalence ratio (**λ**) on the input factors was analyzed using experimental measurements. It was tested with a quadratic polynomial model and the significant terms of λ can be identified from the ANOVA Table 10. The Model F-value of 1247.28 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicates model terms are significant. In this case A, B, AB, A^2, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Table 10. ANOVA for air fuel equivalence ratio (λ)

	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob> F	
Model	0.705462	5	0.141092	1247.279	< 0.0001	significant
A-TIME	0.297483	1	0.297483	2629.791	< 0.0001	
B-EGR	0.129654	1	0.129654	1146.161	< 0.0001	
AB	0.00164	1	0.00164	14.50005	0.0066	
A^2	0.210443	1	0.210443	1860.351	< 0.0001	
B^2	0.003995	1	0.003995	35.32021	0.0006	

It is noticed that the "Pred R-Squared" of 0.9889 is in reasonable agreement with the "Adj R-Squared" of 0.9981. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case the ratio of 112.510 indicates an adequate signal. This model can be used to navigate the design space. The quadratic mathematical correlation of input factors and the NOx emission was developed as shown in Eq.(9).

Air fuel equivalence ratio (λ) = $1.78 - 0.22\,A - 0.15\,B + 0.020\,AB + 0.28\,A^2 + 0.038\,B^2$ (9)

The main effect and interaction effects of λ on the input factor is plotted in Figure 8.(a and b). The plot shows the influence of response on injection time (A) and EGR (B) in its mean level. It is noticed that λ is rapidly decreasing till the mean value of the factor A and then improved whereas the λ is in decreasing trend as the factor B is varied in its specified level.

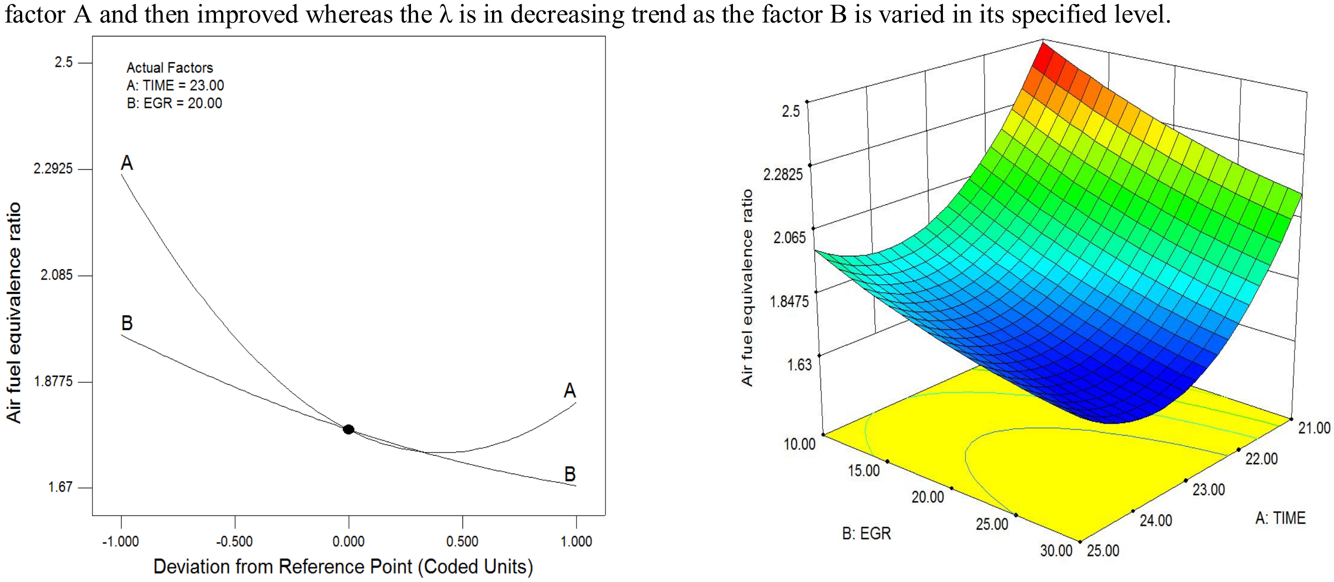

Figure 8.Response plot for λ, (a).Main effect, (b). Interaction effect

It is noticed from the interaction plot that λ is in decreasing trend as the factor B is increased for the entire range of the factor A. The λ reached a maximum value for the lower injection time and lower EGR whereas it has a minimum value when the factors are at its mean level.

6) *Analysis of smoke:* The influence of the input factors on the smoke (FSN) was analyzed using experimental measurements. It was tested with a quadratic polynomial model and the significant terms of smoke can be identified from the ANOVA Table 11. The Model F-value of 1905.53 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicates model terms are significant. In this case A, B, AB, A2, B2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Table 11. ANOVA for smoke (FSN)

	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob> F	
Model	4.06489	5	0.812978	1905.527	< 0.0001	significant
A-TIME	0.589067	1	0.589067	1380.705	< 0.0001	
B-EGR	2.522017	1	2.522017	5911.318	< 0.0001	
AB	0.081225	1	0.081225	190.3821	< 0.0001	
A^2	0.592331	1	0.592331	1388.357	< 0.0001	
B^2	0.038524	1	0.038524	90.29635	< 0.0001	

The "Pred R-Squared" of 0.9933 is in reasonable agreement with the "Adj R-Squared" of 0.9987. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case, the ratio of 137.581 indicates an adequate signal. This model can be used to navigate the design space. The quadratic mathematical correlation of input factors and the NO_x emission was developed as shown in Eq.(10).

$$Smoke = 2.28 - 0.31 A + 0.65 B - 0.14 AB - 0.46 A^2 - 0.12 B^2 \quad (10)$$

The main effect and interaction effects of the input factor on the smoke is plotted in Figure 9.(a and b). The plot shows the influence of response on injection time (A) and EGR (B) in its mean level. It is noticed that smoke is initially increased till the mean value of A and then gradually decreased, whereas the smoke is increased as the factor B is increased.

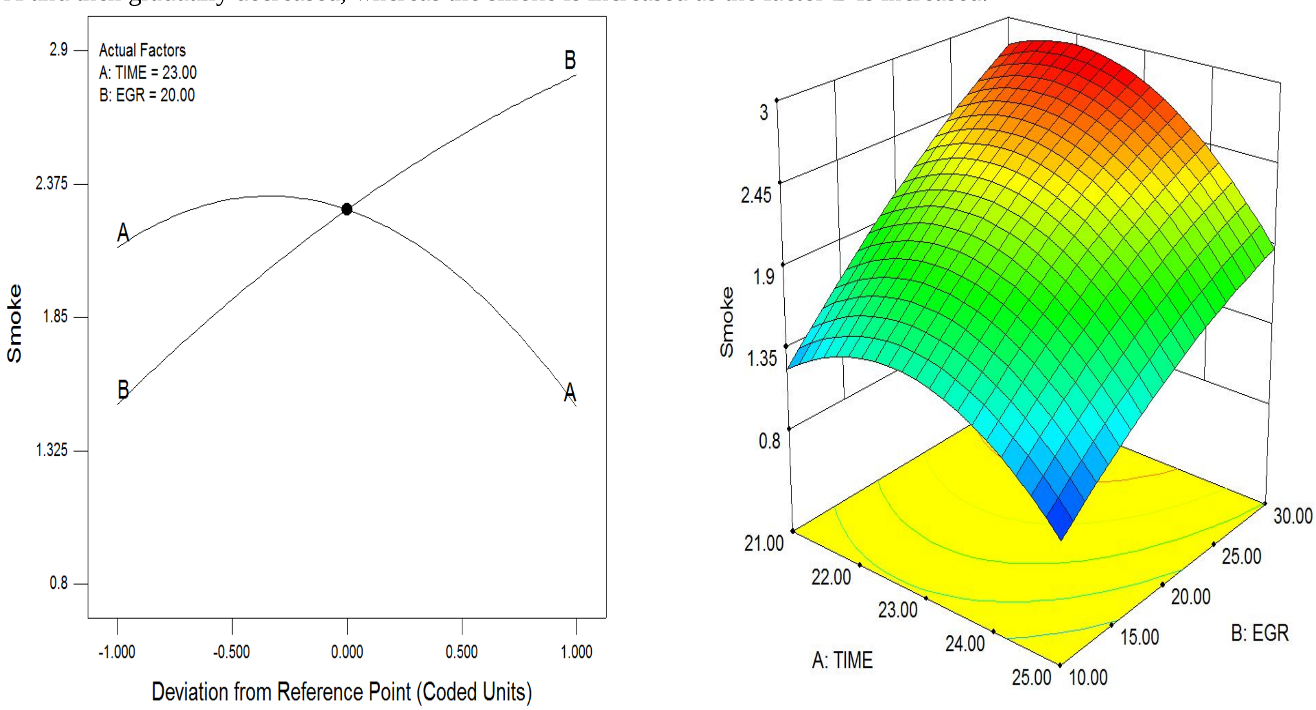

Figure 9.Response plot for smoke, (a).Main effect, (b). Interaction effect

It is noticed from the interaction plot that smoke is in increasing trend as the factor B is varied within its range for all levels of factor A, whereas the smoke increased till the mean value of factor A and then gradually decreased for the specified range.

7) *Analysis of Smoke Density;* The influence of the input factors on the smoke density was analyzed using experimental measurements. It was tested with a quadratic polynomial model and the significant terms of smoke can be identified from the ANOVA Table 12. The Model F-value of 252.71 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case A, B, AB, A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Table 12. ANOVA for smoke density

	Sum of		Mean	F	p-value	
Source	Squares	Df	Square	Value	Prob> F	
Model	8182.974	5	1636.595	252.7095	< 0.0001	significant
A-TIME	1261.5	1	1261.5	194.7904	< 0.0001	
B-EGR	5104.167	1	5104.167	788.1434	< 0.0001	
AB	484	1	484	74.73529	< 0.0001	
A^2	1160.69	1	1160.69	179.2243	< 0.0001	
B^2	0.690476	1	0.690476	0.106618	0.7536	

The "Pred R-Squared" of 0.9439 is in reasonable agreement with the "Adj R-Squared" of 0.9906. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 50.515 indicates an adequate signal. This model can be used to navigate the design space. The quadratic mathematical correlation of input factors and the NO_x emission was developed as shown in Eq.(11).

$$\text{Smoke density} = 66.00 - 14.50\,A + 29.17\,B - 11.00\,AB - 20.50\,A^2 + 0.50\,B^2 \quad (11)$$

The main effect and interaction effects of the input factor on the smoke density is plotted in Figure 10.(a and b). The plot shows the influence of response on injection time (A) and EGR (B) in its mean level. It is noticed that smoke is initially increased till the mean value of A and then gradually decreased, whereas the smoke is increased as the factor B is increased.

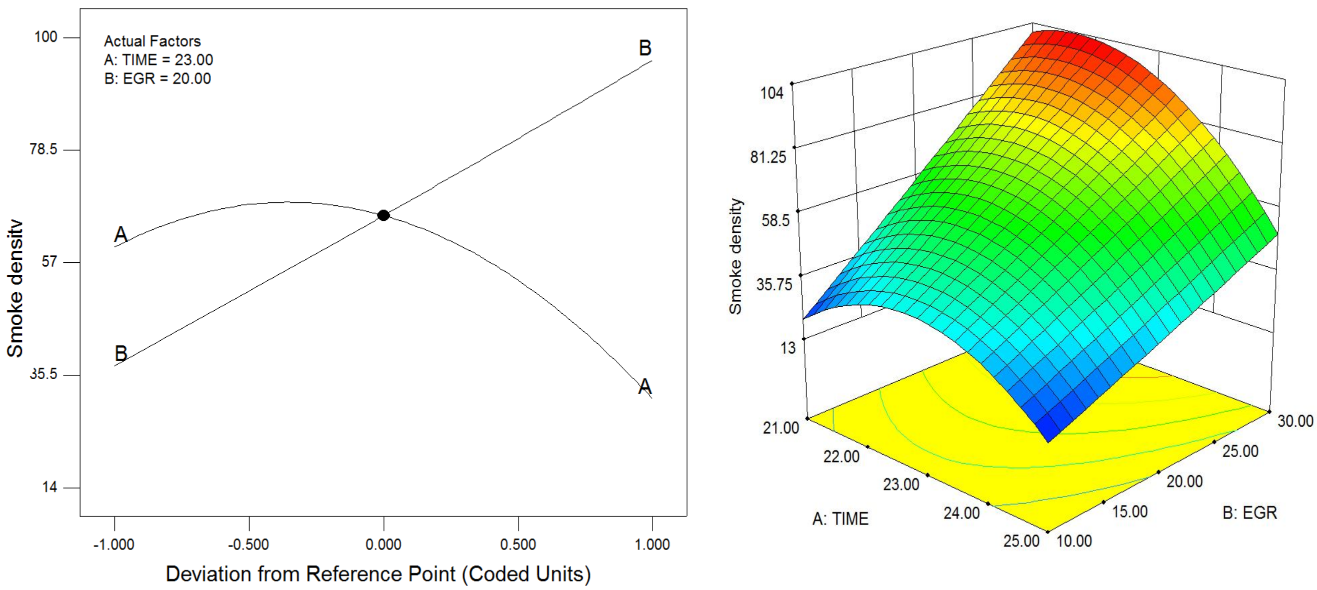

Figure 10.Response plot for smoke density, (a).Main effect, (b). Interaction effect

It is noticed from the interaction plot that smoke density is in increasing trend as the factor B is varied within its range for all levels of factor A, whereas similar to the previous response the smoke density is increased till the mean value of factor A and then gradually decreased for the specified range.

8) *Analysis Of Smoke Opacity:* influence of the input factors on the smoke opacity was analyzed using experimental measurements. It was tested with a quadratic polynomial model and the significant terms of smoke can be identified from the ANOVA Table 13. The Model F-value of 2195.14 implies the model is significant. There is only a 0.01% chance that a "Model

F-Value" this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case A, B, AB, A^2, B^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

Table 13. ANOVA for smoke opacity

	Sum of		Mean	F	p-value	
Source	Squares	Df	Square	Value	Prob> F	
Model	417.4461	5	83.48921	2195.14	< 0.0001	significant
A-TIME	60.80167	1	60.80167	1598.628	< 0.0001	
B-EGR	258.7267	1	258.7267	6802.571	< 0.0001	
AB	8.7025	1	8.7025	228.8105	< 0.0001	
A^2	61.14484	1	61.14484	1607.651	< 0.0001	
B^2	3.68555	1	3.68555	96.90232	< 0.0001	

The "Pred R-Squared" of 0.9945 is in reasonable agreement with the "Adj R-Squared" of 0.9989. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case the ratio of 147.533 indicates an adequate signal. This model can be used to navigate the design space. The quadratic mathematical correlation of input factors and the NO_x emission was developed as shown in Eq.(12).

Smoke opacity $= 19.26 - 3.18 A + 6.57 B - 1.47 AB - 4.71 A^2 - 1.16 B^2$ (12)

The main effect and interaction effects of the input factor on the smoke opacity is plotted in Figure 11.(a and b). The plot shows the influence of response on injection time (A) and EGR (B) in its mean level. It is noticed that smoke opacity is initially increased till the mean value and then gradually decreased beyond this level, whereas the smoke is increased as the factor B is increased.

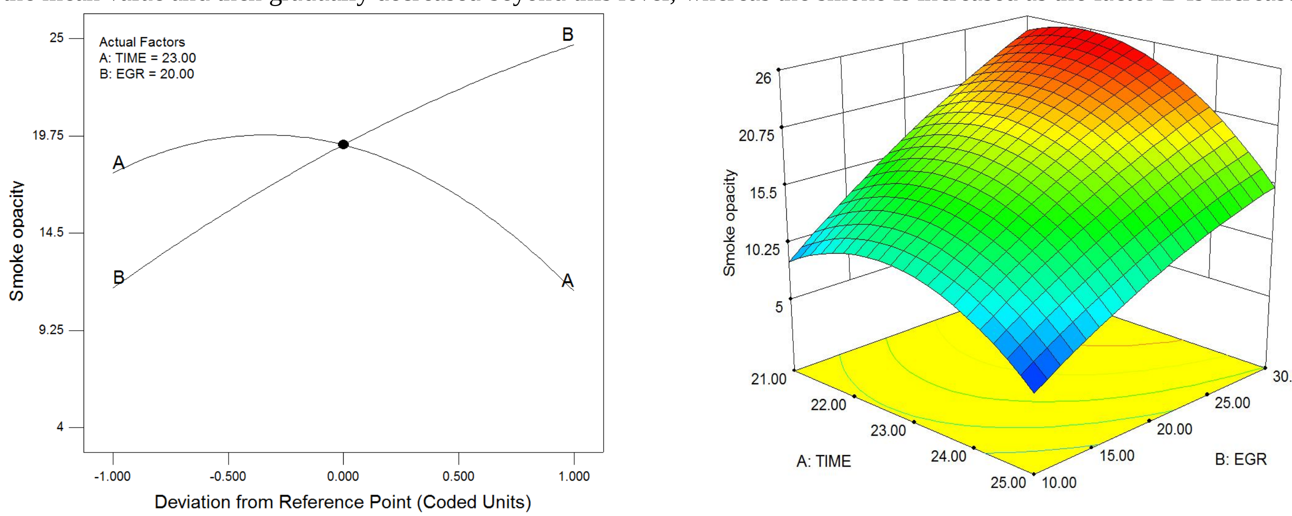

Figure 11.Response plot for smoke opacity, (a).Main effect, (b). Interaction effect

It is noticed from the interaction plot that smoke opacity is in increasing trend as the factor B is varied within its range for all levels of factor A, whereas the smoke opacity is increased till the mean value of factor A and then gradually decreased for the specified range.

V.CONCLUSION

The statistical analysis is significant and engine running with n-butanol/diesel blend under 21°bTDC and 30% EGR had shown positive emission reduction. At 21°bTDC and 30% engine undergoes Low Temperature Combustion (LTC).

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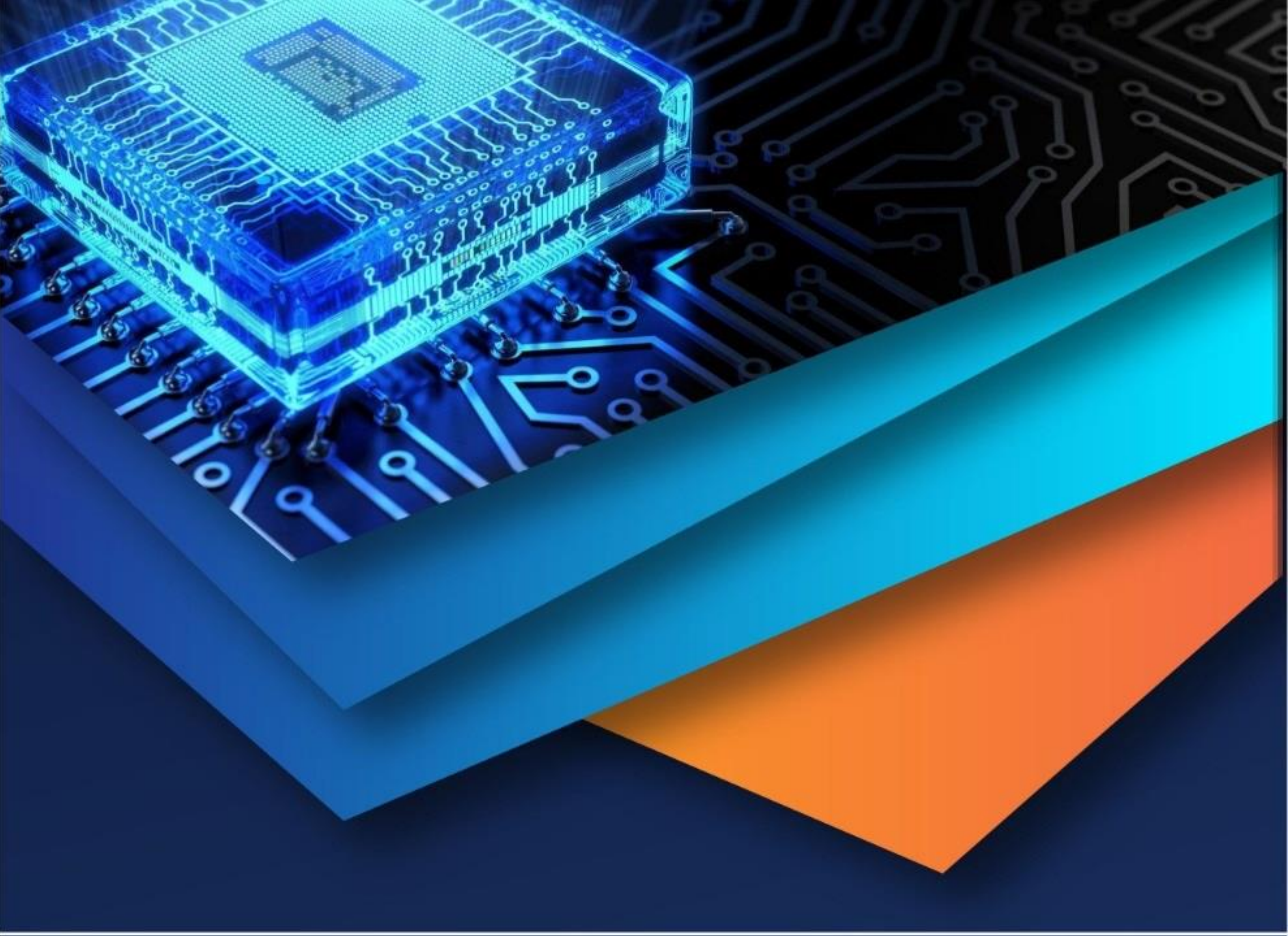

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