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Article *in* Journal of Renewable and Sustainable Energy · June 2013

DOI: 10.1063/1.4811801

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AIP Journal of Renewable and Sustainable Energy

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Citation: J. Renewable Sustainable Energy **5**, 033132 (2013); doi: 10.1063/1.4811801
View online: http://dx.doi.org/10.1063/1.4811801
View Table of Contents: http://jrse.aip.org/resource/1/JRSEBH/v5/i3
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Response surface methodology based prediction of engine performance and exhaust emissions of a diesel engine fuelled with canola oil methyl ester

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(Received 19 January 2013; accepted 7 June 2013; published online 21 June 2013)

The objective of this study was to investigate the effect of fuel injection timing and engine speed on engine performance and exhaust emission parameters using a diesel engine running on canola oil methyl ester (COME). COME was produced by means of the transesterification method and tested at full load with various engine speeds by changing fuel injection timing (12, 15, and 18 °CA) in a turbocharged direct injection (TDI) diesel engine. The experiments were designed using response surface methodology (RSM), which is one of the well-known design of experiment technique for predicting the responses engine performance and exhaust emission parameters from a second order polynomial equation obtained by modeling the relation between fuel injection timing (t) and engine speed (n) parameters. By using the second order full quadratic RSM models obtained from experimental results, responses brake power, brake torque, brake mean effective pressure, brake specific fuel consumption, brake thermal efficiency, exhaust gas temperature, oxygen (O_2), oxides of nitrogen (NO_x), carbon dioxide (CO_2), carbon monoxide (CO), and light absorption coefficient (K) affected from factors t and n were able to be predicted by 95% confidence interval. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4811801]

I. INTRODUCTION

Recently, because of increases in crude oil prices, limited resources of fossil oil, and environmental concerns, there has been a renewed focus on vegetable oils and animal fats to make biodiesel fuels.[1] Canola and soybean are the major feed stocks of biodiesel that are the object of research in Europe and America, respectively.[2,3] Jatropha, karanja, polanga, and other non-edible oils and their methyl esters have also been investigated in many Indian cities.[4–7] As it can be seen from the previous studies, it is evident that there are various problems such as lower energy content, high density and viscosity, iodine value, higher bulk module, and poor volatility of the vegetable oil methyl esters.[8–11] According to the results of the experimental studies, vegetable oil methyl esters offer almost same brake torque and power output, increase in brake specific fuel consumption (because of the lower energy content), and slightly decrease in thermal efficiency compared to those of diesel fuel. There is a general agreement to the fact that the use of biodiesel reduces hydrocarbon (HC), CO, CO_2, and N, while increases NO_x.[12–14]

The combustion process of diesel engine is very complex. The details of the process depend on the combined effect of various parameters like characteristics of the fuel, equivalence ratio, fuel injection timing, injection pressure, combustion chamber and nozzle geometries, etc., and on the engine's operating conditions.[15] Among the operating conditions, engine

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load and speed are the most frequently investigated. Several researchers have also reported that the fuel injection timing and engine speed affects the engine performance and exhaust emissions of diesel engines.[14,16]

Designs of experiment (DOE) techniques are used for modeling and analyzing systems by using experimental results. Response surface methodology (RSM), Taguchi method, and factorial design are well-known and widely used DOE techniques. However, when the literature is reviewed, it is observed that DOE techniques used for fuel injection and diesel engines together are insufficient. RSM is one of the well-known designs of experiment technique for predicting and optimizing the system parameters with minimum number of experiments. It is used for modeling nonlinear relations between the input factors and the responses (outputs). When it is compared with Taguchi method and factorial design, RSM has the advantage that it can be used for optimizing nonlinear systems, which can be modeled by second order full quadratic models and can give optimal solutions with decimals of factor levels while Taguchi gives the optimal combination of factors for the given factor levels and factorial design is appropriate for systems those can be modeled by first order polynomials. The first advantage for using RSM in the present study is that the RSM provides the mathematical relation that also includes the interactions between the factors, which is difficult information to obtain using heuristic optimization techniques. Detection of the interactions between various factors is of critical importance especially for multivariate optimization. The second advantage of RSM is reducing the number of experiments for optimizing processes. Some other mathematical methods may calculate accurate results as done in the case study presented in this paper (for example, direct search, etc) but all other methods except RSM (and other DOE techniques) require more experimental results for accurate mathematical modeling when compared with RSM. When the literature is reviewed for the studies which used RSM together with diesel engines and injection it is observed that the following studies are remarkably related to the subject of the present paper.

Lee and Reitz[17] demonstrated the emission reduction capability of exhaust gas recirculation (EGR) and other parameters on a high-speed direct-injection (HSDI) diesel engine equipped with a common rail injection system using RSM. RSM optimization led engine operating parameters to reach a low-temperature and premixed combustion regime called the modulated kinetics (MK) combustion region, and resulted in simultaneous reductions in NO_x and particulate emissions without sacrificing fuel efficiency. Ricaud and Lavoisier[18] studied on optimizing the multiple injection settings on an HSDI diesel engine by using RSM. Win *et al.*[19] studied the conflicting effects of the operating parameters and the injection parameter (injection timing) on engine performance and environmental pollution factors by using RSM. Reitz and Von der Ehe[20] used a control algorithm incorporated a version of the RSM to adjust the fuel injection parameters and to locate the optimum settings. They designed an engine control algorithm and implemented on a heavy-duty diesel engine. The goal was to develop a control system that could adjust split injection parameters to accommodate changes in operating parameters such as fuel and ambient air conditions, and mechanical wear during engine operation. Laforet *et al.*[21] focused on two techniques—RSM and power law fits—to explore the data for 800 1/min light-load operation with a single injection per cycle, in order to better understand how the ignition process is affected by in-cylinder conditions and the gas/diesel ratio. Perez Peter and Boehman Andre[22] used RSM to determine the relationships between fuel injection timing, engine load, simulated altitude, and oxygen volume fraction to parameters of engine performance, such as power output, brake-specific fuel consumption, and fuel conversion efficiency.

The main purposes of this study are to predict the responses called brake power, brake torque, brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), exhaust gas temperature, O_2, NO_x, CO_2, CO, and K effected from factors t and n. RSM was used for this intention. The investigation represents a combination of numerical and experimental work.

In Sec. II, experimental set-up, the fuel properties of canola oil methyl ester (COME), RSM, and engine test procedure are described. Results and discussion are discussed in Sec. III. Finally, conclusions are defined briefly in Sec. IV.

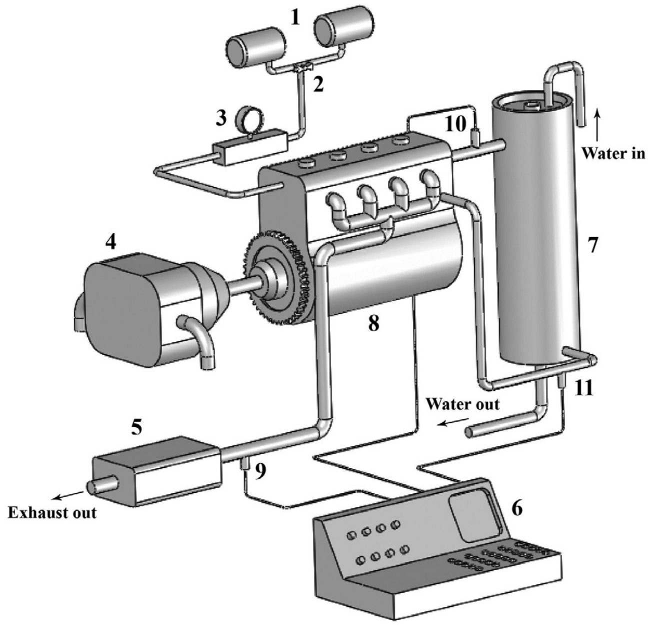

FIG. 1. Experimental setup of the test equipment.

II. MATERIALS AND METHODS

A. Experimental set-up

As shown in Figure 1, the arrangement of the test equipment consisted of a hydraulic dynamometer, a fuel meter, fuel tanks, a cooling water tank, a smoke analyzer, an exhaust gas analyzer, and control panel monitoring systems.

The diesel engine used for the present study was a turbocharged direct injection, four-stroke, four-cylinder engine and the technical specifications are given in Table I.

O_2, NO_x, CO_2, and CO exhaust gases' concentrations were measured as a percentage parts per million (ppm) and $\mu g/m^3$ by Gaco-SN exhaust gas analyzer. For the measurement of K, as a per meter, an OVLT-2600 smoke analyzer was used. The engine dynamometer, which was coupled to the test engine, properties are hydraulic-type (BT-190), with a maximum brake power of 119 kW, a maximum speed of 7500 rpm, a maximum torque of 745 N m, a load cell capacity of 2500 N, and a brake water pressure of 1-2 bar. The engine fuel system was modified by adding a tank fueled with COME, and a two-way, hand-operated control valve, which allowed rapid switching between diesel fuel and COME. A cooling water tank with PT-100 temperature sensor was added to test bench for controlling of cooling water of the engine.

TABLE I. The technical specifications of the test engine.

Model	Land Rover 110
Diameter of cylinders (mm)	90.47
Stroke (mm)	97
Volume (cm^3)	2495
Compression ratio	19.5:1
Maximum torque (Nm) at 2200 rpm	235
Maximum power (kW) at 3800 rpm	82
Maximum speed (rpm)	4400 (+40,−20)
Fuel injection system	Direct injection. turbocharged
Injection pump type	Bosch rotary R509 with mechanical regulator

TABLE II. Fuel properties of diesel fuel and COME.

Property (units)	Testing methods	EN 14214	Diesel	COME
Cetane number	ASTM D613	≥51	49–50	47.2
Kinematic viscosity (mm^2/sn)	ASTM D445	3.5–5	2.6	4.92
Density at 15 °C (g/cm^3)	ASTM D4052-91	0.86–0.90	0.838	0.893
Low heating value (kJ/kg)	ASTM D270	-	43380	39920
Cloud point (°C)	ASTM D2500-91	-	−15	−3
Pour point (°C)	ASTM D6749	-	−23	−13
Flash point (°C)	ASTM D93-94	≥120	67.5	>200
Copper corrosion (at 50 °C, 3 h)	ASTM D130	1a–1b	1a	1a
Acid value (mg of KOH/g)	ASTM D664	0.5–0.8	1.75–3.5	0.48

B. COME fuel

Canola oil, which is used in this experimental investigation, was purchased from an oil supplier. Physical and chemical properties of COME were analyzed according to testing methods given in Table II.

Fatty acid composition of COME was determined according to the biodiesel test method EN 15779, using an Agilent 6890 gas chromatograph. The capillary column was an internal diameter of 0.32 mm, a length of 30 m, and a film thickness of 0.25 μm. Fatty acid composition of methyl ester in COME was illustrated in Table III.

C. Response surface methodology

RSM uses experimental results obtained from orthogonal arrays to model mathematical relations between the factors (inputs) and the responses (outputs). Equation (1) shows the general second-order polynomial response surface mathematical model (full quadratic model) for the experimental design,

$$Y_u = \beta_0 + \sum_{i=1}^{n} \beta_i X_{iu} + \sum_{i=1}^{n} \beta_{ii} X_{iu}^2 + \sum_{i<j}^{n} \beta_{ij} X_{iu} X_{ju} + e_u, \tag{1}$$

where Y_u is the corresponding response, X_{iu} are coded values of the ith input parameters, terms β_0, β_i, β_{ii}, and β_{ij} are the regression coefficients, i and j are the linear and quadratic

TABLE III. Fatty acid composition of COME.

Saturated fatty acids	Fatty acid composition (wt. %)
Myristic (C 14:0)	0.05
Palmitic (C 16:0)	5.07
Heptadecanoic (C 17:0)	0.05
Stearic (C 18:0)	1.75
Arachidic (C 20:0)	0.55
Behenic (C 22:0)	0.36
Lignoceric (C 24:0)	0.13
Unsaturated fatty acids	
Palmitoleic (C 16:1)	0.25
Oleic (C 18:1)	58.4
Gadoleic (C 20:1)	1.22
Erucic (C 22:1)	0.3
Linoleic (C 18:2)	23.42
Linolenic (C 18:3)	8.39

coefficients, and e_u is the residual (experimental error) of the uth observation.[23–26] The model may be written in matrix notation as

$$Y = \beta X + \varepsilon, \quad (2)$$

where Y is the output matrix and X is the input matrix, and ε is the residuals (random error term). The least square estimator of β matrix that composes of coefficients of the regression equation is calculated by the given formula,[23]

$$\beta = (X^T X)^{-1} X^T Y, \quad (3)$$

where the elements of β matrix are the parameters of mathematical model that represents the relationship between the factors and the response in the same order represented in the X matrix.

D. Engine tests

Engine performance and exhaust emission tests were carried out at full load with various engine speeds of 2000, 3000, and 4000 rpm. The engine speed range selected is critical as it is within the acceptable drivability range. Operation of the engine outside this range is unsuitable as a great increase in concentration of exhaust emissions and a decrease in engine torque are obtained when the lower and upper engine speed limits are exceeded. The fuels were tested at three fuel injection timings of 12, 15, and 18 °CA before top dead center (TDC). Optimal fuel injection timing is 15 °CA, while 12 °CA and 18 °CA are later and earlier fuel injection timings, respectively. Fuel injector pressure (200 bar), valve, and fuel delivered pump adjustments were rearranged according to TDI 110's catalogue, and the engine oil was changed before the engine was tested. Engine cooling water temperature was stable between 85 and 90 °C during test period. First, the engine was fuelled with diesel fuel and then COME was employed in diesel engine for engine performance and emissions tests. Engine brake torque, brake power, and hourly fuel consumption values were determined after the engine speed reached a steady state. The emission measurements are possibly affected by atmospheric humidity and temperature variations. Each emission test was performed on the same day to limit day to day deviations in the experimental results. TS ISO 8178-6 test standards were followed for exhaust emission tests.

III. RESULTS AND DISCUSSION

This paper proposes using response surface methodology (RSM), which is one of the well-known design of experiment technique for predicting responses namely brake power, brake torque, BMEP, BSFC, BTE, exhaust gas temperature, O_2, NO_x, CO_2, CO, and K from a second order polynomial equation obtained by modeling the relation between t and n parameters. *RSM* was performed to establish the mathematical relationship between the responses and the input factors. For the modeling, central composite face centered design with one center point, which requires 9 experiments were carried out by using actual values of t and n. Factor levels are given in Table IV.

Because of the nonlinear relations between the mentioned factors, a full quadratic design based on *RSM* was carried out. MINITAB 16 statistical package was used to find the β matrix and establish mathematical models for predicting the previously mentioned responses.

According to the experiments presented in Table V, mathematical models based on *RSM* (presented in Eq. (1) with its general representation) for the responses have been established

TABLE IV. List of actual and corresponding coded values of t and n.

		Level		
Parameter	Symbol	−1	0	1
Fuel injection timing (°CA) before TDC	t	12	15	18
Engine speed (rpm)	n	2000	3000	4000

TABLE V. Design of experiments matrix with the observed responses.

	Coded factor levels		Actual factor levels		Responses										
Exp. No	t (°CA)	n (rpm)	t (°CA)	n (rpm)	Brake power (kW)	Brake torque (Nm)	BTE (%)	Exhaust gas temperature (°C)	BSFC (g/kWh)	BMEP (bar)	O_2 (%)	NO_x (ppm)	CO_2 (%)	CO (ppm)	K (m^{-1})
1	−1	−1	12	2000	48.60	215.70	33.80	408.00	266.13	11.92	8.60	451.00	9.00	725.00	0.44
2	1	−1	18	2000	50.20	224.50	38.58	398.00	233.21	12.31	8.20	464.00	9.40	582.00	0.42
3	−1	1	12	4000	72.90	166.60	27.62	466.00	325.67	8.94	8.00	421.00	10.00	260.00	0.76
4	1	1	18	4000	75.60	171.50	31.55	483.00	285.14	9.27	7.20	442.00	10.30	230.00	0.59
5	−1	0	12	3000	68.20	206.10	32.08	449.00	280.47	11.15	7.60	468.00	9.60	203.00	0.68
6	1	0	18	3000	72.10	215.90	35.68	468.00	252.18	11.79	7.20	483.00	9.90	207.00	0.45
7	0	−1	15	2000	49.60	223.40	38.79	400.00	231.96	12.17	8.20	459.00	9.20	695.00	0.39
8	0	1	15	4000	75.20	170.30	28.98	477.00	310.43	9.22	7.30	425.00	9.80	239.00	0.61
9	0	0	15	3000	71.20	213.80	33.00	459.00	272.59	11.64	7.60	471.00	9.80	249.00	0.46

TABLE VI. Coefficient matrix for the mathematical equations of the responses.

Coefficient	Variables	Brake power	Brake torque	BTE	Exhaust gas temperature	BSFC	BMEP	O_2	NO_x	CO_2	CO	K
β_0	*Constant*	−64.05278	46.308333	19.306944	248.25	344.8677	3.9036528	15.03333	310.22222	8.39166666666666	2895.417	1.710833333
β_1	t	2.625	10.447222	2.1352778	−5.3055556	−10.88142	0.4661389	−0.322222	−9.833333	−0.252777777777777	50.69444	−0.219166667
β_2	n	0.062075	0.0786083	−0.000574	0.1229167	−0.000908	0.003919	−0.002617	0.1576667	0.00144166666666667	−1.766417	0.000275833
β_3	t^2	−0.081481	−0.272222	−0.041296	2×10^{-15}	0.237704	−0.012505	0.011111	0.3518519	0.0111111111111111	−2.944444	0.007777778
β_4	n^2	−0.0000085	−0.0000166	−0.0000004	−0.0000200	0.0000070	−0.0000009	0.0000005	−0.0000303	−0.00000015	0.0002355	0.0000000050
β_5	$t.n$	0.00009	−0.00033	−0.00007	0.00225	−0.000634	−0.000005	−0.000033	0.000667	−0.0000083333	0.009417	−0.000013
	R^2 (%)	99.88	99.91	95.66	99.02	96.72	99.80	94.77	99.31	95.21	99.04	94.50

with 95% confidence interval, and are represented by Eq. (4) and model parameters of Eq. (4) are presented in Table VI with acceptable R^2 values (coefficient of determination),

$$\text{Response} = \beta_0 + \beta_1 \text{t} + \beta_2 n + \beta_3 t^2 + \beta_4 n^2 + \beta_5 t.n. \tag{4}$$

In Table VI, the symbols of model parameters given in Eq. (4) and the factors related to these symbols are given in the first and the second column. Then the values of these model parameters for each response are listed in columns 3–14, respectively. The calculated R^2 values which mean how the response effected from the factors are given at the last row of each

TABLE VII. Analysis of variance (ANOVA) for predicted mathematical models of the responses.

Response	Source	Degrees of freedom (DF)	Sum of squares (SS)	Mean square (MS)	F	P	Result
Brake power (kW)	Regression	5	1101.53	220.31	505.05	0.000	Accept
	Residual error	3	1.31	0.44			
	Total	8	1102.84				
Brake torque (Nm)	Regression	5	4673.48	934.70	633.81	0.000	Accept
	Residual error	3	4.42	1.48			
	Total	8	4677.90				
BTE (%)	Regression	5	114.30	22.86	13.24	0.029	Accept
	Residual error	3	5.18	1.73			
	Total	8	119.48				
Exhaust gas temperature (°C)	Regression	5	9161.58	1832.32	60.80	0.003	Accept
	Residual error	3	90.42	30.14			
	Total	8	9252.00				
BSFC (g/kWh)	Regression	5	7860.55	1572.11	17.68	0.020	Accept
	Residual error	3	266.83	88.94			
	Total	8	8127.37				
BMEP (bar)	Regression	5	15.32	3.06	302.11	0.000	Accept
	Residual error	3	0.03	0.01			
	Total	8	15.35				
O_2 (%)	Regression	5	1.93	0.39	10.87	0.039	Accept
	Residual error	3	0.11	0.04			
	Total	8	2.04				
NO_x (ppm)	Regression	5	3509.11	701.82	86.13	0.002	Accept
	Residual error	3	24.44	8.15			
	Total	8	3533.56				
CO_2 (%)	Regression	5	1.28	0.26	11.93	0.034	Accept
	Residual error	3	0.06	0.02			
	Total	8	1.34				
CO (ppm)	Regression	5	390366.00	78073.00	61.83	0.003	Accept
	Residual error	3	3788.00	1263.00			
	Total	8	394154.00				
K (m^{-1})	Regression	5	0.13	0.03	10.30	0.042	Accept
	Residual error	3	0.01	0.00			
	Total	8	0.14				

TABLE VIII. Design of experiments matrix with the observed responses and fitted responses.

Experiment No	Coded factor levels t (°CA)	Coded factor levels n (rpm)	Actual factor levels t (°CA)	Actual factor levels n (rpm)	Responses: Brake power (kW)	Fitted brake power (kW)	Brake torque (Nm)	Fitted brake torque (Nm)	BTE (%)	Fitted BTE (%)	Exhaust gas temperature (°C)	Fitted exhaust gas temperature (°C)	BSFC (g/kWh)	Fitted BSFC (g/kWh)	BMEP (bar)	Fitted BMEP (bar)
1	−1	−1	12	2000	48.60	48.13	215.70	215.49	33.80	34.67	408.00	404.42	266.13	259.54	11.92	11.85
2	1	−1	18	2000	50.20	50.31	224.50	225.28	38.58	39.20	398.00	399.58	233.21	229.43	12.31	12.34
3	−1	1	12	4000	72.90	72.68	166.60	165.71	27.62	27.42	466.00	464.25	325.67	326.66	8.94	8.90
4	1	1	18	4000	75.60	75.96	171.50	171.59	31.55	31.10	483.00	486.42	285.14	288.94	9.27	9.32
5	−1	0	12	3000	68.20	68.89	206.10	207.20	32.08	31.41	449.00	454.33	280.47	286.08	11.15	11.26
6	1	0	18	3000	72.10	71.62	215.90	215.03	35.68	35.51	468.00	463.00	252.18	252.17	11.79	11.72
7	0	−1	15	2000	49.60	49.96	223.40	222.83	38.79	37.30	400.00	402.00	231.96	242.34	12.17	12.21
8	0	1	15	4000	75.20	75.06	170.30	171.10	28.98	29.63	477.00	475.33	310.43	305.66	9.22	9.22
9	0	0	15	3000	71.20	70.99	213.80	213.57	33.00	33.83	459.00	458.67	272.59	266.99	11.64	11.60

Experiment No	Coded factor levels t (°CA)	Coded factor levels n (rpm)	Actual factor levels t (°CA)	Actual factor levels n (rpm)	Responses: O_2 (%)	Fitted O_2 (%)	NO_x (ppm)	Fitted NO_x (ppm)	CO_2 (%)	Fitted CO_2 (%)	CO (ppm)	Fitted CO (ppm)	K (m^{-1})	Fitted K (m^{-1})
1	−1	−1	12	2000	8.60	8.53	451.00	452.89	9.00	9.04	725.00	714.92	0.44	0.47
2	1	−1	18	2000	8.20	8.20	464.00	465.22	9.40	9.43	582.00	602.08	0.42	0.41
3	−1	1	12	4000	8.00	7.90	421.00	420.22	10.00	9.93	260.00	234.08	0.76	0.78
4	1	1	18	4000	7.20	7.17	442.00	440.56	10.30	10.21	230.00	234.25	0.59	0.57
5	−1	0	12	3000	7.60	7.77	468.00	466.89	9.60	9.63	203.00	239.00	0.68	0.62
6	1	0	18	3000	7.20	7.23	483.00	483.22	9.90	9.97	207.00	182.67	0.45	0.48
7	0	−1	15	2000	8.20	8.27	459.00	455.89	9.20	9.13	695.00	685.00	0.39	0.37
8	0	1	15	4000	7.30	7.43	425.00	427.22	9.80	9.97	239.00	260.67	0.61	0.61
9	0	0	15	3000	7.60	7.40	471.00	471.89	9.80	9.70	249.00	237.33	0.46	0.48

column. For example, R^2 value of 99.88 that is calculated for brake power at the end of the third column means that the factors t and n can explain the change in brake power with 99.88%. The rest of the change $(100\% - 99.88\% = 0.12\%)$ is affected from other factors that are not placed in the mathematical model. Analysis of variance (ANOVA) table is given in Table VII.

Engine performance parameters and exhaust emissions test results predicted from the mathematical model are given in Table VIII under the fitted values columns.

A. Engine performance parameters

By using the mathematical relations (which the coefficients are presented in Table VI and Eq. (2)), the surface plots were plotted in Figures 2–12. It is clearly observed from Figures 2–7 that the brake power, brake torque, BMEP, BSFC, BTE, and exhaust gas temperature are highly affected from fuel injection timing and engine speeds.

As the injection timing advanced from 12 °CA to 18 °CA, the brake torque, brake power, BMEP, BTE, and exhaust gas temperature were increased, while the BSFC decreased. This is explained in that long ignition delay occurs at early fuel injection timing (18 °CA) because of low charge temperature and pressure in the cylinders. In this situation, the amount of fuel that is ready to burn increases and a more homogeneous mixture is achieved. If fuel injection timing is retarded (12 °CA), first cylinder pressure and temperature are high, it is because of extension combustion to reach to the exhaust period, cylinder pressure and temperature begin to decrease. It is seen in Figures 2–7, brake torque, brake power, BMEP, BTE, and exhaust gas temperature values at 12 °CA fuel injection timing are low compared to those of 18 °CA fuel injection timing for all experiments. The general trend is that at later fuel injection timing the peak heat release rate decreases and the combustion event occurs over a longer period of time.[16] If fuel injection starts later (closer to TDC), the temperature and pressure are initially slightly higher but then decrease as the delay proceeds.[15] A long period of time for combustion results in excessive heat loss, a decrease in maximum combustion chamber pressure, and a decrease in indicated brake torque, brake power, BMEP, BTE, and exhaust gas temperature.

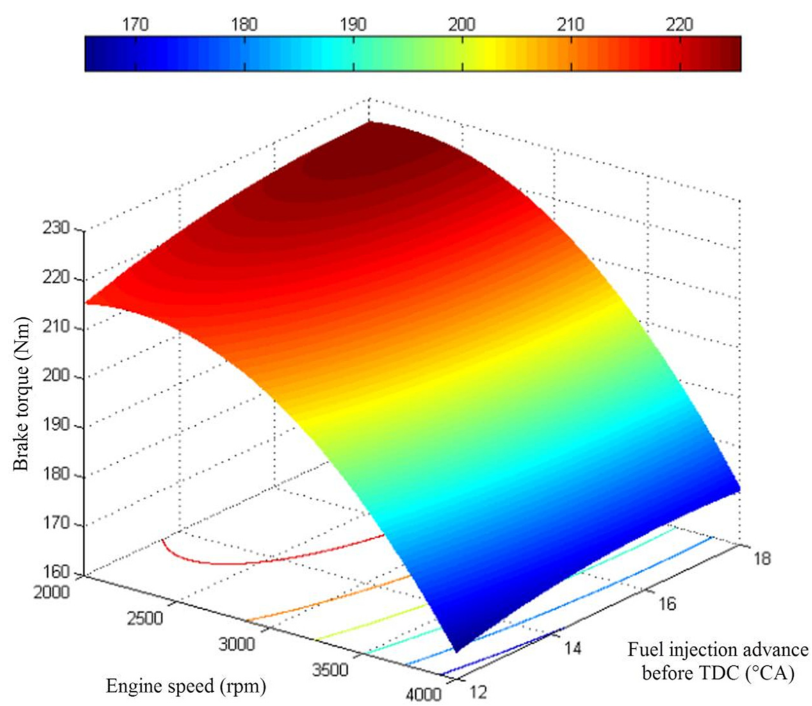

FIG. 2. Three dimensional plot showing the effect of t and n and their mutual effect on the brake torque.

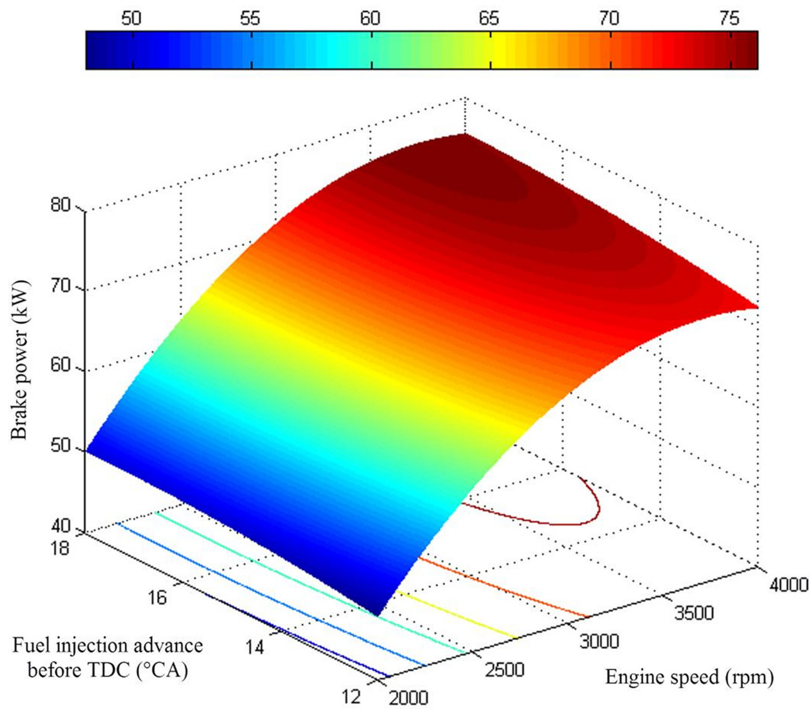

FIG. 3. Three dimensional plot showing the effect of t and n and their mutual effect on the brake power.

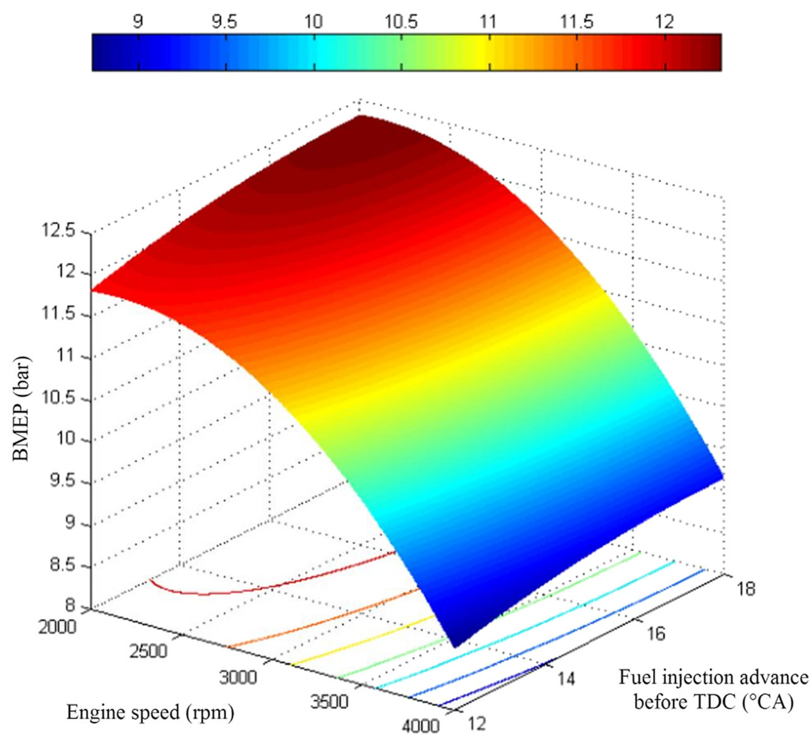

FIG. 4. Three dimensional plot showing the effect of t and n and their mutual effect on the BMEP.

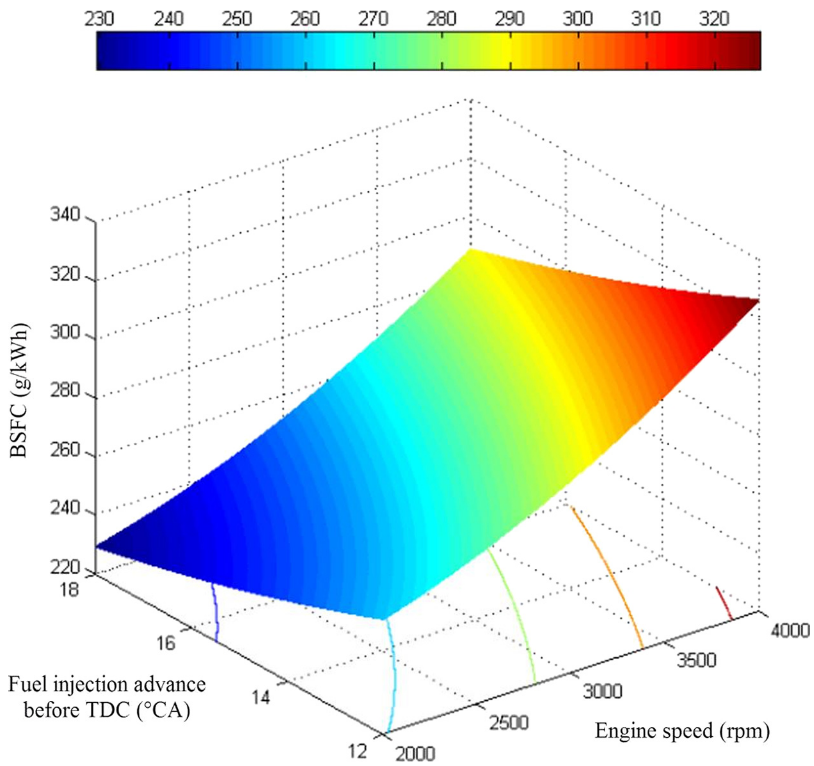

FIG. 5. Three dimensional plot showing the effect of t and n and their mutual effect on the BSFC.

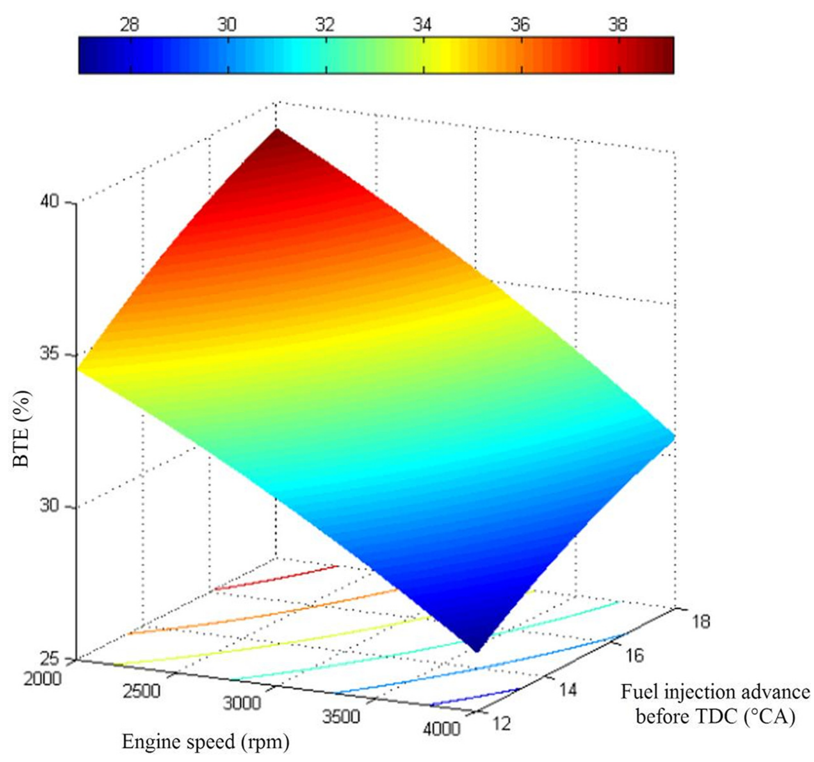

FIG. 6. Three dimensional plot showing the effect of t and n and their mutual effect on the BTE.

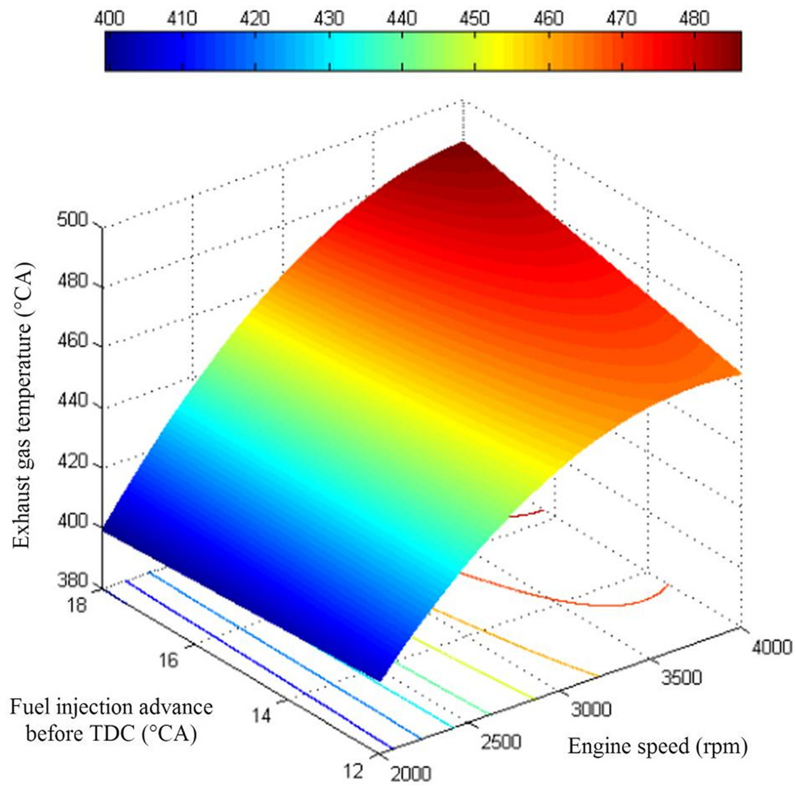

FIG. 7. Three dimensional plot showing the effect of t and n and their mutual effect on the exhaust gas temperature.

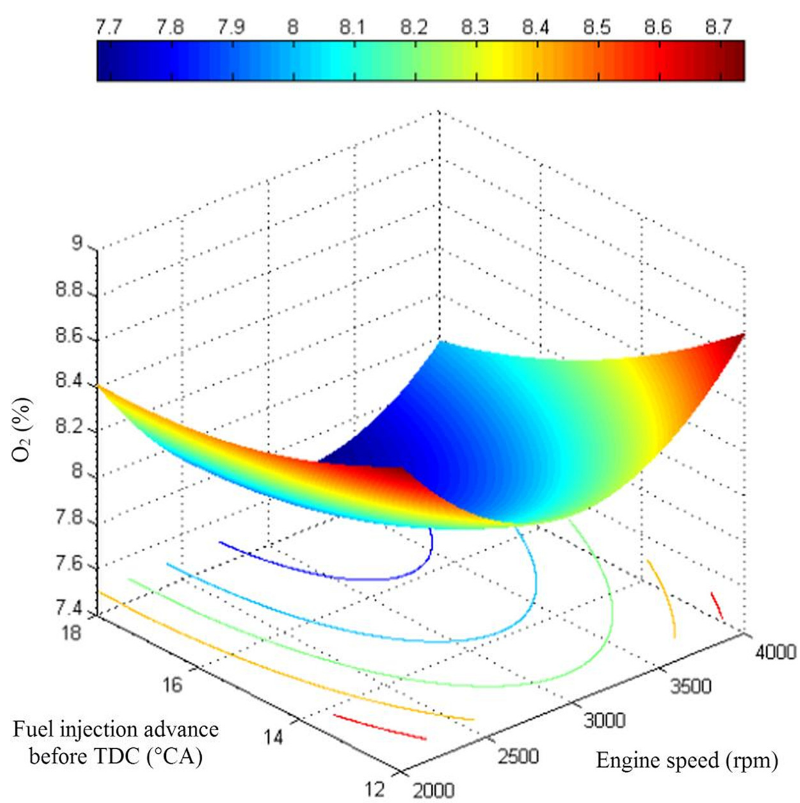

FIG. 8. Three dimensional plot showing the effect of t and n and their mutual effect on the O_2.

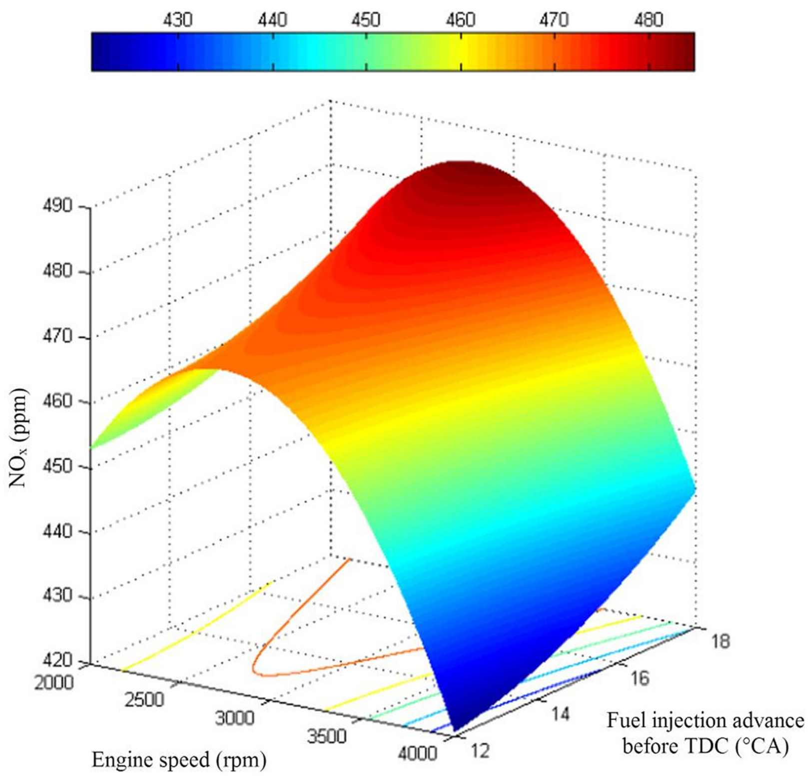

FIG. 9. Three dimensional plot showing the effect of t and n and their mutual effect on the NO_x.

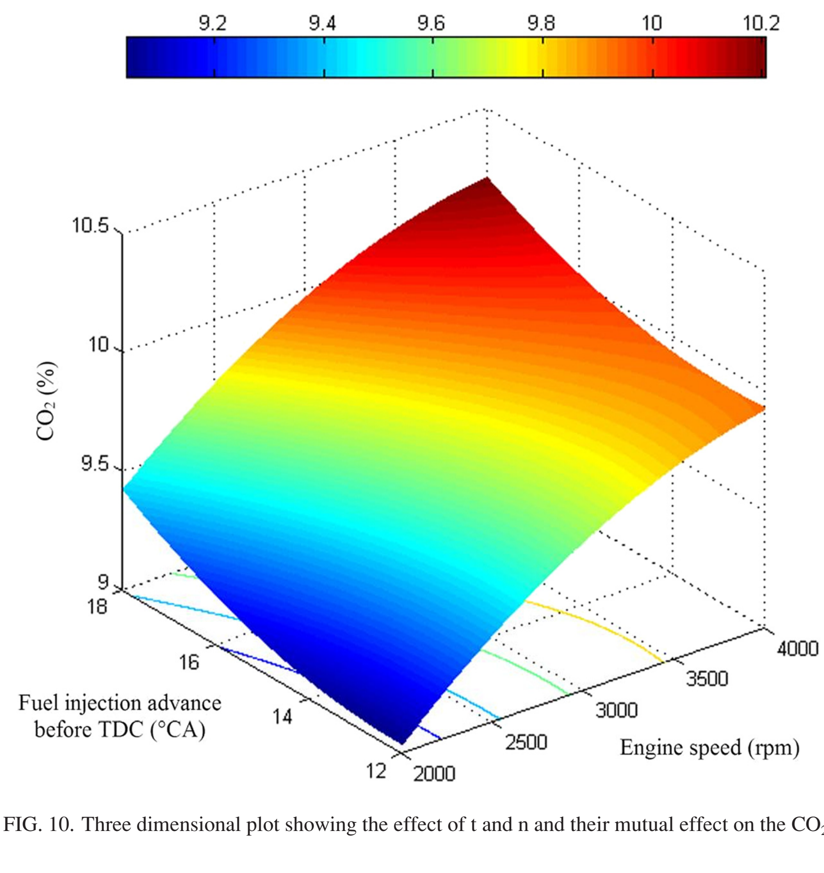

FIG. 10. Three dimensional plot showing the effect of t and n and their mutual effect on the CO_2.

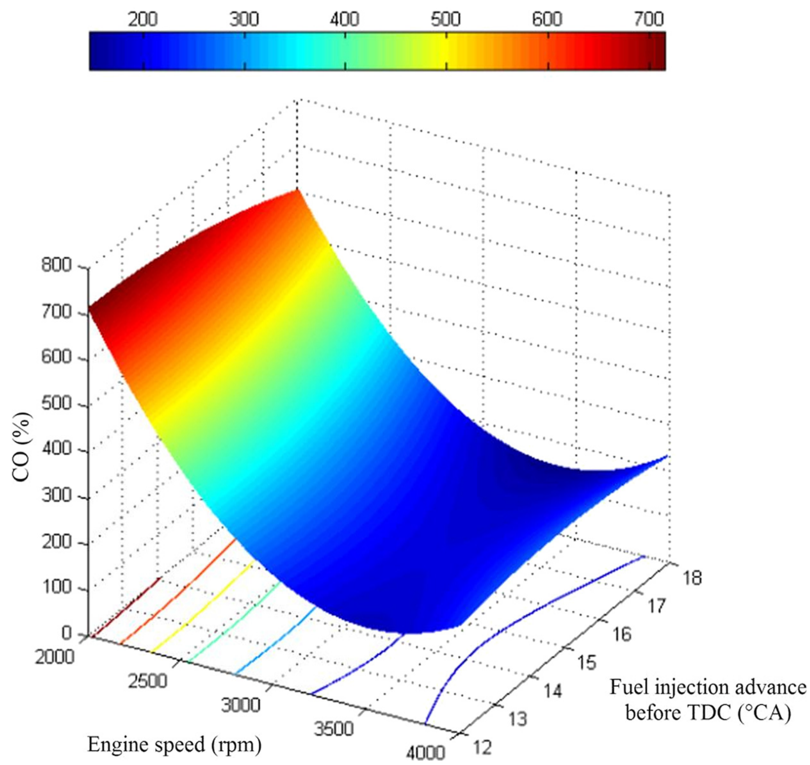

FIG. 11. Three dimensional plot showing the effect of t and n and their mutual effect on the CO.

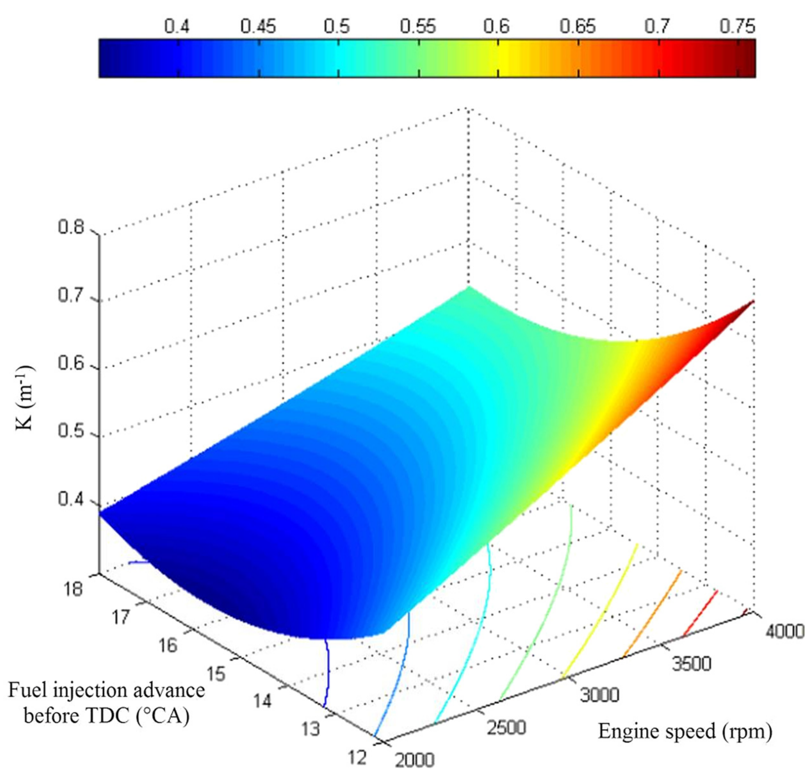

FIG. 12. Three dimensional plot showing the effect of t and n and their mutual effect on the K.

TABLE IX. Comparisons for the observed and fitted response values for the check data set (confirmation tests).

	Actual factor levels		Responses											
Exp. No	t (°CA)	n (rpm)	Brake power (kW)	Fitted brake power (kW)	Brake torque (Nm)	Fitted brake torque (Nm)	BTE (%)	Fitted BTE (%)	Exhaust gas temperature (°C)	Fitted exhaust gas temperature (°C)	BSFC (g/kWh)	Fitted BSFC (g/kWh)	BMEP (bar)	Fitted BMEP (bar)
10	12	3500	71.90	72.91	185.30	190.60	30.55	29.51	497.00	464.29	294.53	304.62	10.08	10.30
11	12	2500	58.00	60.63	215.70	215.50	34.97	33.13	430.00	434.38	257.24	271.06	11.38	11.78
12	12	1750	42.80	40.29	217.10	212.38	39.15	35.37	396.00	385.69	229.81	255.09	12.00	11.72
13	15	3500	75.80	75.14	198.10	196.48	32.27	31.82	437.00	472.00	278.83	284.57	10.62	10.63
14	15	2500	62.00	62.59	224.00	222.35	35.17	35.66	431.00	435.33	255.79	252.91	12.17	12.13
15	15	1750	43.90	42.05	226.00	219.96	39.11	38.06	389.00	381.58	230.03	238.37	12.31	12.08
16	18	3500	77.80	75.91	200.10	197.46	32.17	33.40	494.00	479.71	279.63	268.80	10.90	10.74
17	18	2500	62.40	63.09	225.00	224.30	37.17	37.45	434.00	436.29	242.07	239.04	12.25	12.25
18	18	1750	44.20	42.34	226.90	222.65	39.77	40.00	388.00	377.48	226.24	225.93	12.39	12.22

Confirmation tests

	Actual factor levels		Responses									
Exp. No	t (°CA)	n (rpm)	O_2 (%)	Fitted O_2 (%)	NO_x (ppm)	Fitted NO_x (ppm)	CO_2 (%)	Fitted CO_2 (%)	CO (ppm)	Fitted CO (ppm)	K (m^{-1})	Fitted K (m^{-1})
10	12	3500	6.50	7.72	455.00	451.14	10.00	9.82	189.00	177.67	0.66	0.70
11	12	2500	8.60	8.04	460.00	467.47	9.00	9.38	394.00	418.08	0.54	0.55
12	12	1750	8.10	8.87	446.00	439.91	9.50	8.85	645.00	907.49	0.50	0.44
13	15	3500	6.70	7.30	465.00	457.14	10.20	9.87	167.00	190.13	0.57	0.54
14	15	2500	8.20	7.72	463.00	471.47	9.30	9.45	325.00	402.29	0.44	0.43
15	15	1750	8.20	8.62	447.00	442.41	9.90	8.94	649.00	870.51	0.57	0.34
16	18	3500	6.80	7.09	456.00	469.47	10.30	10.13	129.00	149.58	0.54	0.52
17	18	2500	7.40	7.60	467.00	481.81	9.80	9.73	329.00	333.50	0.43	0.44
18	18	1750	8.10	8.58	478.00	451.24	9.30	9.24	575.00	780.53	0.67	0.39

These results are similar to those of Kannan and Anand,[27] who fueled a TV1-KIRLOSKAR engine with neat diesel and biodiesel from waste cooking oil. From their study, Kanan and Anand[27] concluded that the effect of injection timing on ignition delay is more dominant than injection pressure.

Increasing of engine speed from 2000 rpm to 4000 rpm, the brake power, exhaust gas temperature, and BSFC were increased and brake torque, BTE, and BMEP decreased. A change in engine speed changes the temperature/time and pressure/time relationships. As speed increases, injection pressure also increases in mechanical fuel injection systems. The peak compression temperature increases with increasing speed due to smaller heat loss during the compression stroke.[15] Figure 7 shows that exhaust gas temperature increases as the engine speed is increased. Similar results are reported by Sayin *et al.*[28] and Ng *et al.*[29]

Engine performance parameters and exhaust emissions' test results predicted from the mathematical model given in Table VIII and Eq. (1) are compared with those obtained by experiments in Table IX for 12 sets of check data. It can be concluded from the results that predictions can be performed with an acceptable error ratio with less effort by using *RSM*. The fitness ratios are given in Table X for the best and worse fitted responses as follows: 99.13 and 94.14 (%) for brake power, 99.91 and 97.14 (%) for brake torque, 99.42 and 90.34 (%) for BTE, 99.47 and 91.99 (%) for exhaust gas temperature, 99.86 and 88.99 (%) for BSFC, and 100 and 96.49 (%) for BMEP. Details are given in Table X.

B. Exhaust emissions

Variations of exhaust emissions versus engine speed and fuel injection timing are displayed in Figures 8–12. Figures 8–12 revealed that the O_2, CO, and K were decreased while the CO_2 and NO_x were increased on the advancement of injection timing from 12 °CA to 18 °CA at all engine speeds.

If carbon (C) atoms in the fuel partially react with O_2 molecules in the combustion chamber, percentages of CO, O_2, and K emissions in the exhaust gas increases. Full combustion of a fuel requires in existence the amount of stoichiometric oxygen. However, the amount of stoichiometric oxygen generally is not enough for full combustion because the fuel is not oxygenated. The structural oxygen content of fuel increases the combustion efficiency of the fuel due to increased mixing of oxygen with the fuel during combustion.[30]

CO_2, which is also called greenhouse gas, is a chemical product of complete combustion reactions and is a component of ambient air. High CO_2 and NO_x levels in the exhaust emissions indicate that burned gases are fully reacted. Figures 9 and 10 points out that by advancing the fuel injection timing, NO_x and CO_2 emissions slightly increase. In addition, CO_2 and K

TABLE X. Fitness ratios for expected and observed responses.

	Actual factor levels		Responses											
Exp. No	t (°CA)	n (rpm)	Brake power (kW)	Brake torque (Nm)	BTE (%)	Exhaust gas temperature (°C)	BSFC (g/kWh)	BMEP (bar)	O_2 (%)	NO_x (ppm)	CO_2 (%)	CO (ppm)	K (m^{-1})
10	12	3500	98.60	97.14	96.60	93.42	96.57	97.82	81.23	99.15	98.20	94.01	93.94
11	12	2500	95.47	99.91	94.74	98.98	94.63	96.49	93.49	98.38	95.78	93.89	98.15
12	12	1750	94.14	97.83	90.34	97.40	89.00	97.67	90.49	98.63	93.16	59.30	88.00
13	15	3500	99.13	99.18	98.61	91.99	97.94	99.91	91.04	98.31	96.76	86.15	94.74
14	15	2500	99.05	99.26	98.61	99.00	98.87	99.67	94.15	98.17	98.39	76.22	97.73
15	15	1750	95.79	97.33	97.32	98.09	96.37	98.13	94.88	98.97	90.30	65.87	59.65
16	18	3500	97.57	98.68	96.18	97.11	96.13	98.53	95.74	97.05	98.35	84.05	96.30
17	18	2500	98.89	99.69	99.25	99.47	98.75	100.00	97.30	96.83	99.29	98.63	97.67
18	18	1750	95.79	98.13	99.42	97.29	99.86	98.63	94.07	94.40	99.35	64.26	58.21

emissions increased with the increase in engine speeds. Previous studies by Koçak *et al.*[1] and Ng *et al.*[29] showed similar results.

With increase in engine speed, the time of the combustion process is reduced. Thus, incomplete combustion leads to reduction in combustion efficiency and increase in K emissions.

The fitness ratios are given in Table X for the best and worse fitted responses as follows: 97.30 and 81.23 (%) for O_2, 99.15 and 94.40 (%) for NO_x, 99.35 and 90.30 (%) for CO_2, 98.63 and 59.30 (%) for CO, and 99.29 and 61.38 (%) for K. Details are given in Table X.

IV. CONCLUSION

By using response surface methodology, an empirical relationship was developed to predict engine performance and exhaust emissions of a diesel engine fuelled with canola oil methyl ester. The developed mathematical model can be effectively used to predict the brake power, brake torque, BMEP, BSFC, BTE, exhaust gas temperature, O_2, NO_x, CO_2, CO, and K. The results show that *RSM* is an effective tool for this purpose. R-squared values that were calculated for brake power, brake torque, BTE, exhaust gas temperature, BSFC, BMEP, O_2, NO_x, CO_2, CO, and K are 99.88, 99.91, 95.66, 99.02, 96.72, 99.80, 94.77, 99.31, 95.21, 99.04, and 92.56%, respectively.

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