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Effect of Number of Injector Nozzle Holes on the Performance, Emission and Combustion Characteristics of Honge Oil Biodiesel (HOME) Operated DI Compression Ignition Engine

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Abstract

This paper aims to present the inferences of the experimental studies on the performance, emission and combustion characteristics of Honge oil methyl ester (HOME) as a fuel for a single-cylinder direct injection diesel engine using response surface methodology (RSM) based mathematical modeling which are developed taking 27 set of experimental results. Experiments were carried out to study the effects of compression ratio, injection pressure and injection timing on performance characteristics like brake thermal efficiency (BTE), emissions such as smoke, hydrocarbon (HC), carbon monoxide (CO), nitric oxides (NO_x) and combustion characteristics, namely, peak pressure and heat release rate (HRR) in a diesel engine using 3 and 4 hole injectors. The experiments were planned as per full factorial design (FFD) and RSM based quadratic models were developed to establish the relationships between the process parameters and the proposed characteristics. The response surface analysis based on the experimental results reveal that by retarding the injection timing (IT), increasing the injector-opening pressure (IOP) as well as the compression ratio would lead to increased BTE and reduced emissions. Increasing the number of nozzle holes improves the performance of diesel engine fueled with HOME in terms of increased BTE, reduced emissions like smoke, HC, CO and increased peak pressure and HRR. However, NO_x emission increases with increased number of holes.

Keywords: Honge oil methyl ester; Performance characteristics; Emission characteristics; Combustion characteristics; Design of experiments; Response surface methodology

Introduction

The vegetable oils and their esters are the most suited substitute fuels for diesel engine applications as they have lower emission levels with comparable thermal efficiency [1-13]. However, the atomization of biodiesel is poor due to its higher viscosity (almost twice the diesel). Biodiesels can replace diesel fuel completely however it being less volatile needs to be blended with other low viscosity fuels such as diesel or ethanol to get better performance [14,15]. The higher viscosity of biodiesel prompts it to be injected at higher IOP to improve the fuel injection and atomization characteristics thereby improving the combustion quality [16-20]. In compression ignition (CI) engines, the peak cylinder pressure depends on the fraction of burned fuel during the premixed burning phase or uncontrolled combustion phase. The IOP characterizes the ability of the fuel to mix well with surrounding air and undergo complete combustion [13,16]. It was reported that increased injection pressure caused increased NO_x concentrations, while soot concentrations were decreased [21]. CI engines when operated using different vegetable oils showed improved performance at higher compression ratio [22,23]. The amount of heat released in the premixed combustion of a CI engine depends on the ignition delay, fuel air mixing rate and the calorific value of the fuel [24]. Improvement in the heat release characteristics and reduction in ignition delay with higher compression ratio were also reported [25,26].

Advancing IT increased NO_x and BTE, while lowered HC, CO, smoke opacity due to decreased in-cylinder charge temperature and pressure [27-29]. Impact of split injection strategy on the exhaust emissions and soot particulates from a CI engine fueled with neat biodiesel has been reported [10]. Several researchers have investigated the effect of nozzle hole geometry on the performance of diesel engines and have observed that increasing the number of injector nozzle holes increased the HRR during pre-mixed as well as mixing controlled combustion phases [16,20,30] and an increased indicated power, torque and specific fuel consumption for all speeds have also been reported [30]. However, the effect of nozzle hole geometry on biodiesel fuelled engine performance has not been investigated using RSM based models which were developed taking experimental results.

This paper discusses the effect of number of nozzle holes on the performance, emission and combustion characteristics of a single-cylinder direct injection diesel engine fueled with HOME for different ITs, injection pressures and the compression ratios. The traditional technique necessitates the variation of one factor at a time (OFAT) approach, wherein the other factors are maintained at preset levels and hence is time consuming. Besides, the traditional method needs enormous number of experiments and also does not consider the interactive effects among the factors. On the other hand, RSM based mathematical modeling using design of experiments (DOE) is found to be a capable modeling tool [31,32]. The RSM is not only useful in reducing the cost and time but also furnishing the decisive information

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about the interaction effects of factors. Hence, an effort has been made in the present study to build the RSM based quadratic models of performance, emission and combustion characteristics with experiments planned as per FFD. The effects of compression ratio, injection pressure and injection timing on performance characteristic like BTE, emission characteristics such as smoke, HC, CO, NO_x and combustion characteristics, namely, peak pressure and HRR have been analyzed for 3 and 4 hole injectors by developing second order RSM based mathematical models.

Methodology

The RSM is a mathematical modeling device, mainly used for building up the correlation among the control factors and the proposed response(s). The RSM is helpful for improving and optimizing the product/process, which largely offers a perspective of the response(s) within the intended space [31,32]. The modeling of desired response(s) to various factors can be obtained through DOE and applying the regression analysis. The DOE provides an opportunity to study not only the individual effects of each factor but also the interactions for achieving the optimum conditions. Hence, RSM adopts both the mathematical and statistical methods to describe the influence of interactions of factors on response(s) when they are varied simultaneously. In many circumstances, it is probable to represent the independent factors in quantitative form and these factors can be thought of having a functional relation or response that can be expressed as [31,32]:

$$Y = \phi(x_1, x_2, x_3, \ldots\ldots x_n) \quad (1)$$

where, Y is the output, are the control factors and is the response function. It can be approximated within the experimental region by a polynomial when the mathematical form of the response function is unknown.

Experimental Details

Design of experiments

The planning of experiments is important for constructing mathematical models based on RSM. The modeling presents reliable equations attained through DOE. In the present work the compression ratio (R), injection pressure (P) and IT (θ) are identified as the process parameters to assess the performance characteristic BTE (η), emission characteristics such as smoke, HC, CO, NO_x and combustion characteristics, namely, peak pressure (P_{max}) and HRR. Since, the factors identified are multi-level parameters and their end effects are not linearly related as per the authors' preliminary studies; hence it was decided to use multi-level tests for the process parameters. Three levels were selected for each of the identified parameters and their effects on the proposed characteristics were tested through a set of planned experiments based on FFD to investigate the quadratic response surface [31,32] and hence, 27 trials based on FFD were planned. The identified parameters and their defined levels are shown in Table 1 and the experimental layout for the present investigation is given in Table 2.

Experimentation and measurement of performance, emission and combustion characteristics

A four-stroke single cylinder water cooled direct injection CI engine was used to perform the experiments, which is equipped with a displacement volume of 662 cc, compression ratio of 17.5:1 and developing 5.2 kW power at 1500 rpm. The modified test rig for operating on a single fuel mode with HOME is illustrated in Figure 1; the specifications of the engine are presented in Table 3. The engine is equipped with a traditional fuel injection system, which was operated at a rated speed of 1500 rpm throughout the experimentation period. As specified by the manufacturer during the experimentation the static IT and the IOP were kept at 23° BTDC and 205 bar respectively. The engine was provided with a hemispherical combustion chamber with overhead valves operated through push rods. The cooling of the engine was accomplished by circulating the water through the jackets on the engine block and cylinder head.

To measure the cylinder pressure, piezoelectric pressure transducer was mounted on the cylinder head surface. The present work involves the experimental studies on the effect of three engine parameters, namely compression ratio, injection pressure and IT on the performance of diesel engine operated on HOME. The various properties of the HOME used are exhibited in Table 4. The IT, injection pressure and compression ratio were varied as per the FFD plan (Table 2). Each trial was repeated six times and the average was taken as the process response. For the measurement of exhaust emissions, exhaust gas analyzer and smoke meter were used; the specifications of which are given in Tables 5 and 6 respectively.

The performance, emission and combustion characteristics values are summarized in Table 7. This experimental database was then used to build the RSM based quadratic models.

Development of RSM Based Models

In the current study, each controllable parameter was investigated at three levels to explore the non-linearity effects and hence, second order RSM based mathematical models for BTE (η), smoke, HC, CO, NO_x, peak pressure (P_{max}) and HRR have been constructed with compression ratio (R), injection pressure (P) and IT (θ) as the process parameters. The quadratic mathematical model is of the form [31,32]:

$$Y = b_0 + b_1R + b_2P + b_3\theta + b_{11}R^2 + b_{22}P^2 + b_{33}\theta^2 + b_{12}RP + b_{13}R\theta + b_{23}P\theta \quad (2)$$

Parameter	Levels		
Compression ratio (R)	15.5	16.5	17.5
Injection pressure (P), bar	220	230	240
Injection timing (θ), degree	19	23	27

Table 1: Identified parameters and their levels.

Trial no.	Process parameter settings		
	Compression ratio	Injection pressure (bar)	Injection timing (degree)
1	15.5	220	19
2	15.5	220	23
3	15.5	220	27
4	15.5	230	19
5	15.5	230	23
6	15.5	230	27
7	15.5	240	19
8	15.5	240	23
9	15.5	240	27
10	16.5	220	19
11	16.5	220	23
12	16.5	220	27
13	16.5	230	19
14	16.5	230	23
15	16.5	230	27
16	16.5	240	19
17	16.5	240	23
18	16.5	240	27
19	17.5	220	19
20	17.5	220	23
21	17.5	220	27
22	17.5	230	19
23	17.5	230	23
24	17.5	230	27
25	17.5	240	19
26	17.5	240	23
27	17.5	240	27

Table 2: Experimental layout plan.

Sl No	Parameter	Specifications
1	Machine supplier	Apex Innovations Pvt Ltd. Sangli, Maharashtra, India
2	Type	TV1 (Kirloskar make)
3	Software used	Engine soft
4	Nozzle opening pressure	200 to 225 bar
5	Governor type	Mechanical centrifugal type
6	No of cylinders	Single cylinder
7	No of strokes	Four stroke
8	Fuel	H. S. Diesel
9	Rated power	5.2 KW (7 HP) @1500 RPM
10	Cylinder diameter (Bore)	0.0875 mtr
11	Stroke length	0.11 mtr
12	Compression ratio	17.5: 1
	Air Measurement Manometer	
13	Make	MX 201
14	Type	U- Type
15	Range	100 – 0 – 100 mm
	Eddy current dynamometer	
16	Model	AG – 10
17	Type	Eddy current
18	Maximum	7.5 KW at 1500 to 3000 RPM
19	Flow	Water must flow through Dynamometer during the use
20	Dynamometer arm length	0.180 mtr
21	Fuel measuring unit – Range	0 to 50 ml

Table 3: Specifications of CI engine.

Figure 1: Compression ignition engine test rig employed in the current investigation.

Sl. No.	Properties	Diesel	Honge oil	HOME
1	Chemical Formula	$C_{13}H_{24}$	----	----
2	Density (kg/m³)	840	915	880
3	Calorific value (kJ/kg)	43,000	35800	36,010
4	Viscosity at 40°C (cSt)	2-5	44.85	5.5
5	Flashpoint (°C)	65	210	167
6	Cetane Number	45-55	40	45
7	Carbon Residue (%)	0.1	0.66	----
8	Cloud point	-2	----	7
9	Pour point	-5	----	4
10	Carbon residue	0.13	0.55	0.01
11	Molecular weight	181		227
12	Auto ignition temperature (°C)	260		470
13	Ash content % by mass	0.57		0.01
14	Oxidation stability	High	Low	Low
15	Sulphur Content	High	No	No

Table 4: Properties of HOME.

Type	DELTA 1600S
Object of measurement	Carbon monoxide (CO), Carbon Dioxide (CO_2) and Hydrocarbons (HC)
Range of measurement	HC = 0 to 20,000 ppm as C_3H_8 (Propane) CO = 0 to 10% CO_2 = 0 to 16% O_2 = 0 to 21% NO_X = 0 to 5000 ppm (as Nitric Oxide)
Accuracy	HC = ± 30 ppm HC CO = ± 0.2% CO CO_2 = ± 1% CO_2 O_2 = ± 0.2% O_2 NO_X = ± 10 ppm NO
Resolution	HC = 1 ppm CO = 0.01% Vol. CO_2 = 0.1% Vol. O_2 = 0.01% Vol. NO_X = 1 ppm
Warm up time	10 min. (self controlled) at 20°C
Speed of response time	Within 15 sec. for 90% response
Sampling	Directly sampled from tail pipe
Power source	100 to 240 V AC/50 Hz
Weight	800 gm
Size	100 mm×210 mm×50 mm

Table 5: Specifications of exhaust gas analyzer.

Type	Hartridge Smokemeter-4
Object of measurement	Smoke
Measuring range opacity	0-100%
Accuracy	± 2% relative
Resolution	0.1%
Smoke length	0.43 m
Ambient Temperature Range	-5°C to + 45°C
Warm up time	10 min. (self controlled) at 20°C
Speed of response time	Within 15 sec. for 90% response
Sampling	Directly sampled from tail pipe
Power Supply	100 to 240 V AC / 50HZ 10 – 16 V DC @15 amps
Size	100 mm×210 mm×50 mm

Table 6: Specifications of smoke meter.

Trial no.	3 hole injector							4 hole injector						
	Brake thermal efficiency (%)	Smoke (HSU)	HC (ppm)	CO (%)	NO_x (ppm)	P_{max} (bar)	HRR (J/°CA)	Brake thermal efficiency (%)	Smoke (HSU)	HC (ppm)	CO (%)	NOx (ppm)	P_{max} (bar)	HRR (J/°CA)
1	24	76	88	0.33	600	52	44	25	72	81	0.3	607	54	44
2	25.5	72	80	0.3	615	55	48	26.5	66	76	0.26	622	57	51
3	25	74	84	0.31	625	58	52	26	70	79	0.28	632	60	56
4	22	90	91	0.36	975	54	46	23	84	87	0.33	963	57	47
5	23.5	80	85	0.32	1000	57	50	24.5	75	81	0.28	982	60	53
6	23	87	87	0.34	1010	60	54	24	80	84	0.3	996	62	57
7	21.5	95	102	0.41	1045	48	40	22.5	90	99	0.37	1055	50	42
8	22.75	90	95	0.36	1075	50	42	23.75	84	92	0.33	1095	52	44
9	22.25	92	98	0.38	1105	53	48	23.25	88	95	0.35	1120	55	52
10	26	71	81	0.29	625	57	46	27	68	77	0.26	625	60	48
11	27	67	75	0.25	635	59	52	28	63	70	0.22	635	62	54
12	26.5	69	78	0.26	645	61	55	27.5	65	74	0.24	645	64	59
13	25	81	84	0.3	1010	58	48	26	77	80	0.28	1010	61	50
14	26.5	75	78	0.27	1022	60	56	27.5	70	75	0.24	1030	64	58
15	26	79	81	0.29	1030	63	60	27	73	77	0.26	1040	68	62
16	24.5	85	95	0.35	1105	50	43	25.5	80	91	0.33	1105	52	47
17	26	80	86	0.31	1135	52	47	27	74	81	0.28	1143	54	50
18	25.5	82	90	0.33	1175	55	52	26.5	78	84	0.3	1168	59	56
19	27	64	70	0.17	800	60	50	28	60	66	0.15	820	62	52
20	28	60	65	0.15	825	62	55	29	55	60	0.13	830	64	60
21	27.5	62	67	0.16	840	64	60	28.5	58	62	0.14	860	67	63
22	26	72	75	0.19	1020	62	52	27	66	77	0.16	960	63	55
23	27	66	60	0.16	1029	65	58	28	62	71	0.14	1000	67	62
24	26.5	68	68	0.17	1033	68	62	27.5	64	74	0.15	1065	70	66
25	25.5	79	79	0.2	1030	55	46	26.5	76	72	0.19	1525	58	48
26	26.75	70	75	0.18	1060	58	51	27.5	67	68	0.17	1555	60	53
27	26	74	77	0.19	1090	60	55	27	72	70	0.18	1620	62	57

Table 7: Measured values of Performance, emission and combustion characteristics.

where, Y: response, i.e., η, smoke, HC, CO, NOx, Pmax and HRR.; b0,........,b23 : regression coefficients of models are to be determined for each of the responses. The regression coefficients of the proposed models are calculated as [31,32]:

$$B=(X^TX)^{-1}X^TY \tag{3}$$

where, B: matrix of parameter estimates; X: calculation matrix, which includes linear, quadratic and interaction terms, X^T: transpose of X and Y: matrix of response. The RSM based non-linear mathematical models as determined by regression analysis to predict η, smoke, HC, CO, NOx, Pmax and HRR for 3 hole and 4 hole injectors are given by:

Three hole injector

$$\begin{aligned}\eta &= -724.52+32.09896{*}R+4.350174{*}P-2.62587{*}\theta\text{-}0.90278{*}R^2-0.00903{*}P^2+0.021701{*}\theta^2\\ &\quad -0.01042{*}R{*}P+0.078125{*}R{*}\theta+0.000521{*}P{*}\theta\end{aligned} \tag{4}$$

$$Smoke = 2085.65 + 19.375{*}R - 19.9368{*}P + 15.84722{*}\theta - 0.38889{*}R^2 + 0.044444{*}P^2 - 0.11806{*}\theta^2 - 0.025{*}R{*}P - 0.375{*}R{*}\theta - 0.01042{*}P{*}\theta \quad (5)$$

$$HC = 2342.27 + 88.7083{*}R - 24.9354{*}P - 3.89583{*}\theta - 2.77778{*}R^2 + 0.053889{*}P^2 + 0.232639{*}\theta^2 - 0.29167{*}R{*}\theta - -0.00208{*}P{*}\theta \quad (6)$$

$$CO = 5.244572 + 1.051111{*}R - 0.11496{*}P + 0.027292{*}\theta - 0.03444{*}R^2 + 0.000239{*}P^2 + 0.000451{*}\theta^2 + 0.00025{*}R{*}P - 0.0025{*}R{*}\theta \quad (7)$$

$$NO_x = -10306.6 + 348.2361{*}R + 5.247917{*}P + 586{*}\theta + 0.722222{*}R^2 - 0.01611{*}P^2 - 7.73611{*}\theta^2 - 0.05833{*}R{*}P - 13.9583{*}R{*}\theta + 0.21875{*}P{*}\theta \quad (8)$$

$$P_{max} = -20.1829 - 13.0903{*}R - 0.02847{*}P + 12.10069{*}\theta + 0.611111{*}R^2 + 0.001111{*}P^2 - 0.29514{*}\theta^2 - 0.01667{*}R{*}P + 0.020833{*}R{*}\theta + 0.002083{*}P{*}\theta \quad (9)$$

$$HRR = -324.64 + 2.715278{*}R + 1.099306{*}P + 13.34375{*}\theta - 0.27778{*}R^2 - 0.00278{*}P^2 - 0.29861{*}\theta^2 + 0.041667{*}R{*}P + 0.020833{*}R{*}\theta - 0.00208{*}P{*}\theta \quad (10)$$

Four hole injector

$$\eta = -714.743 + 32.66319{*}R + 4.222396{*}P - 2.50347{*}\theta - 0.91667{*}R^2 - 0.00875{*}P^2 + 0.020833{*}\theta^2 - 0.01042{*}R{*}P + 0.072917{*}R{*}\theta + 0.000521{*}P{*}\theta \quad (11)$$

$$Smoke = 2551.775 + 11.41667{*}R - 22.8354{*}P + 8.993056{*}\theta - 0.38889{*}R^2 + 0.049444{*}P^2 - 0.05556{*}\theta^2 - 0.25{*}R{*}\theta - 0.00208{*}P{*}\theta \quad (12)$$

$$HC = 1947.42 + 48.86111{*}R - 20.6806{*}P + 15.42361{*}\theta - 1.33333{*}R^2 + 0.045{*}P^2 - 0.05208{*}\theta^2 - 0.58333{*}R{*}\theta - -0.00833{*}P{*}\theta \quad (13)$$

$$CO = 6.965359 + 1.007569{*}R - 0.12608{*}P + 0.011007{*}\theta - 0.03389{*}R^2 + 0.000261{*}P^2 + 0.000694{*}\theta^2 + 0.000333{*}R{*}P - 0.0018{*}R{*}\theta \quad (14)$$

$$NO_x = 31034.38 - 3237.48{*}R - 28.2333{*}P - 194.941{*}\theta + 83.61111{*}R^2 + 0.017778{*}P^2 - 1.49306{*}\theta^2 + 0.975{*}R{*}P + 16.27083{*}R{*}\theta + 0.2875{*}P{*}\theta \quad (15)$$

$$P_{max} = -198.855 + 17.85417{*}R - 0.79236{*}P + 13.20486{*}\theta - 0.44444{*}R^2 + 0.002222{*}P^2 - 0.31944{*}\theta^2 + 0.020833{*}R{*}\theta + 0.002083{*}P{*}\theta \quad (16)$$

$$HRR = -755.11 + 18.72222{*}R + 3.252778{*}P + 17.13889{*}\theta - 0.33333{*}R^2 - 0.005{*}P^2 - 0.29167{*}\theta^2 - 0.00833{*}R{*}P - 0.08333{*}R{*}\theta - 0.0125{*}P{*}\theta \quad (17)$$

where, P in bar, θ in degree, brake thermal efficiency (η) in %, smoke in HSU; HC in ppm, CO in % and NO_x in ppm, Pmax in bar and HRR in J/0CA.

The statistical testing of the developed quadratic models was tested through F-test for the analysis of variance (ANOVA) [31,32]. As per ANOVA, the computed value of F-ratio of the constructed model should be more than F value given in the table for the model to be adequate. Table 8 represents the ANOVA results of the developed models and found to be significant at 99% confidence interval as F-ratio of all the models is greater than 3.68 (F- table (9, 17, 0.01)). The adequacy of the models is also verified through coefficient of determination (R^2) [31,32] that provides a measure of variability in the observed values of the response and can be explained by the parameters and their interactions. The R^2 values are given in Table 7, which show a good correlation between the experimental and the predicted values of the proposed characteristics. Hence, these quadratic models (Equations 4-17) are used to predict the characteristics by substituting the values of IT, injection pressure and compression ratio within the ranges of the process parameters selected.

Results and Discussion

The effects of process parameters on performance, emmision and combustion characteristics for 3 hole and 4 hole injectors are presented in Figures 2-22. These plots were generated considering two parameters at a time, while the third parameter was kept at the center level.

Characteristic	Sum of squares		Degrees of freedom		Mean square		F-ratio	R^2
	Regression	Residual	Regression	Residual	Regression	Residual		
Brake thermal efficiency	80.6545	1.3084	9	17	8.9616	0.0770	116.43	0.984
Smoke	2280.72	30.91	9	17	253.41	1.82	139.39	0.987
HC	2730.19	44.99	9	17	303.35	2.65	114.62	0.984
CO	0.158831	0.00071	9	17	0.017648	0.000042	422.44	0.996
NO_x	886280	28830	9	17	98476	1696	58.07	0.968
P_{max}	626.278	8.019	9	17	69.586	0.472	147.53	0.987
HRR	837.806	14.269	9	17	93.090	0.839	110.91	0.983

$F\text{- table}_{(9, 17, 0.01)} = 3.68$

a) 3 hole injector

Characteristic	Sum of squares		Degrees of freedom		Mean square		F-ratio	R^2
	Regression	Residual	Regression	Residual	Regression	Residual		
Brake thermal efficiency	79.8924	1.3993	9	17	8.8769	0.0823	107.84	0.983
Smoke	2091.64	37.55	9	17	232.40	2.21	105.23	0.982
HC	2210.00	154.67	9	17	245.56	9.10	26.99	0.935
CO	0.136506	0.000569	9	17	0.015167	0.000033	453.54	0.996
NO_x	1822126	152580	9	17	202458	8975	22.56	0.923
P_{max}	667.278	16.130	9	17	74.142	0.949	78.14	0.976
HRR	991.08	25.58	9	17	110.12	1.50	73.17	0.975

$F\text{- table}_{(9, 17, 0.01)} = 3.68$

b) 4 hole injector

Table 8: ANOVA results and R^2 values of mathematical models of performance, emission and combustion characteristics

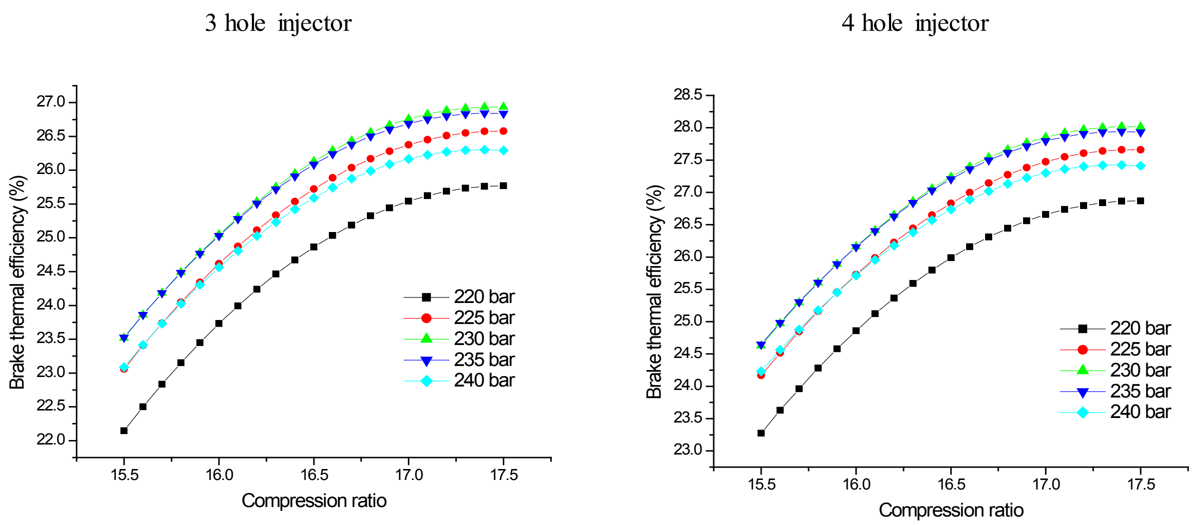

Figure 2: Interaction effect of compression ratio and injection pressure on brake thermal efficiency.

Effect of process parameters on performance characteristic

Brake thermal efficiency: The interaction effects of compression ratio and injection pressure on BTE for three hole and four hole injectors are depicted in Figure 2. It is observed from the figure that, for any specified value of injection pressure, the BTE increases with the increase in compression ratio. The probable reason for this behavior might be, the combustion temperature increases with increased compression ratio leading to higher flame temperature. These experimental results closely agree with the results reported by Raheman and Ghadge [22] and Laguitton et al. [23]. However, it is revealed from the figure that, with further increase in the injection pressure (in the range of 220-235 bar), the BTE increases with the increase in the compression ratio. The higher BTE achieved at 230-bar pressure is largely due to the improved atomization, spray characteristics and air -fuel mixing, which results in better combustion. It is seen from our experimental results that increasing the number of holes from 3 to 4 results in increased BTE for the same compression ratio and injection pressure but for higher values of injection pressure (240 bar), the BTE decreases. HOME being more viscous than diesel (almost twice), the injected biodiesel droplets will be larger for the same injection pressure and compression ratio and consequently increased number of holes will make sure proper mixing of the injected fuel i.e., HOME with the surrounding air. Therefore, 4 hole injector operation results in an improved fuel combustion process. It also produces a comparatively more homogeneous

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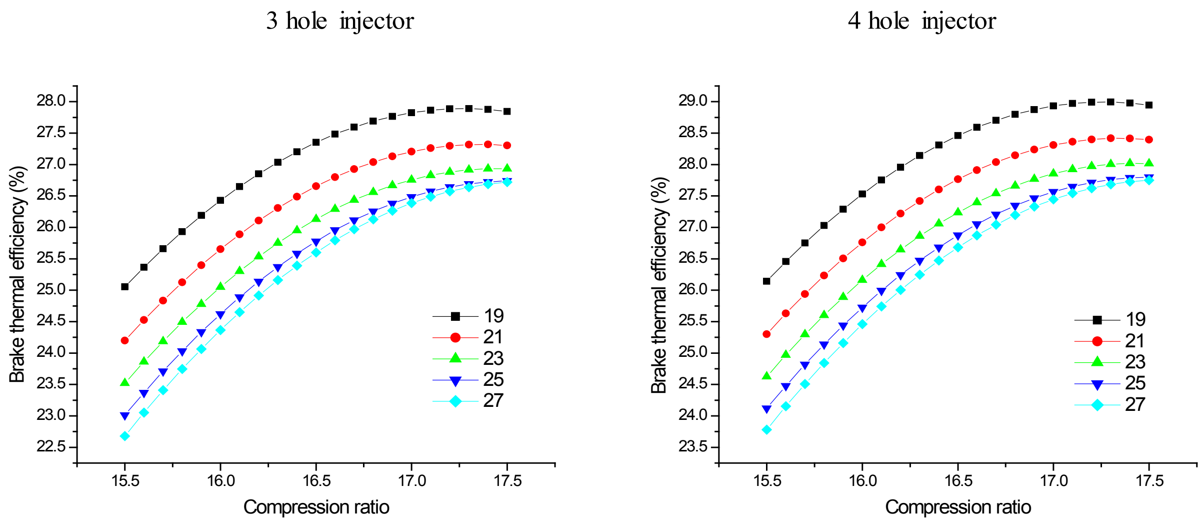

Figure 3: Interaction effect of compression ratio and injection timing on brake thermal efficiency.

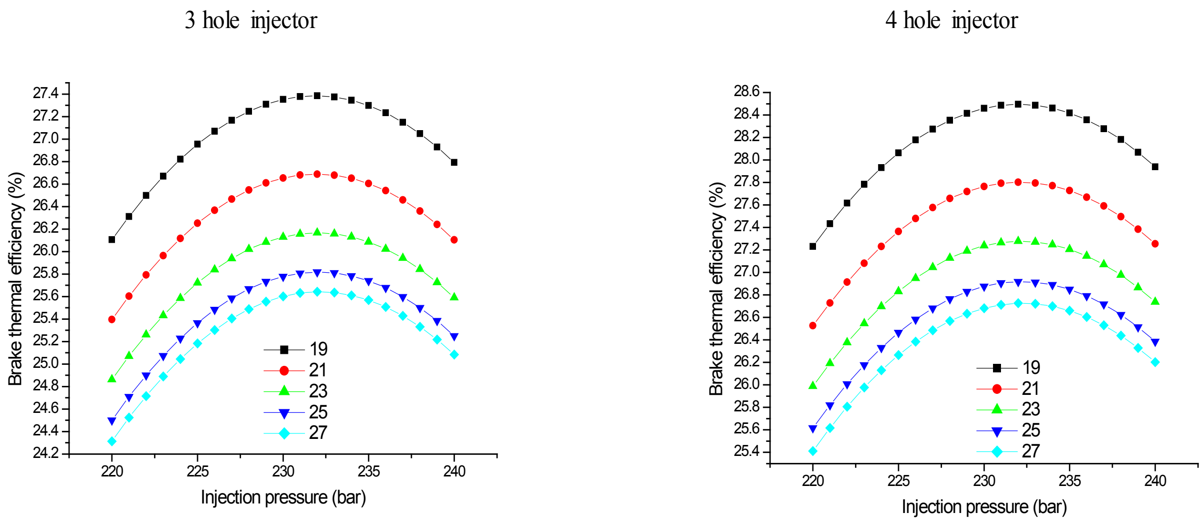

Figure 4: Interaction effect of injection pressure and injection timing on brake thermal efficiency.

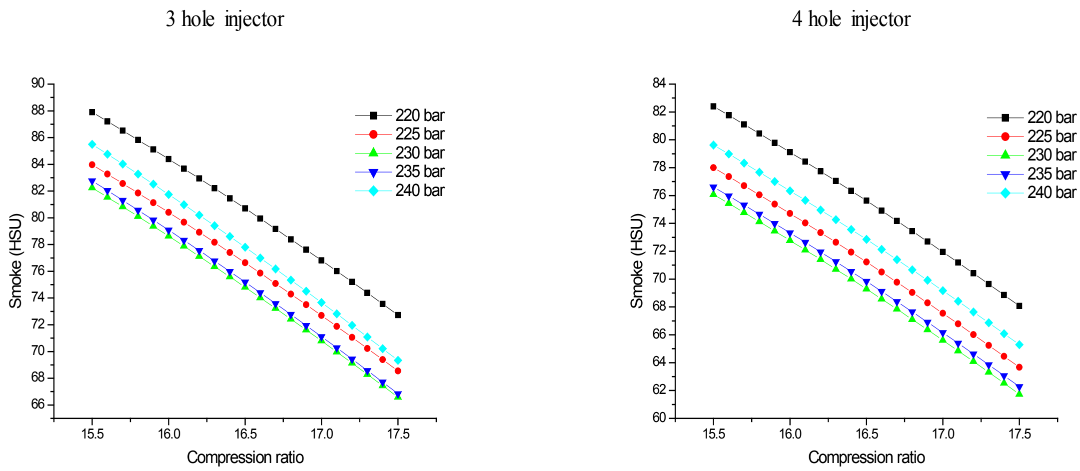

Figure 5: Interaction effect of compression ratio and injection pressure on smoke.

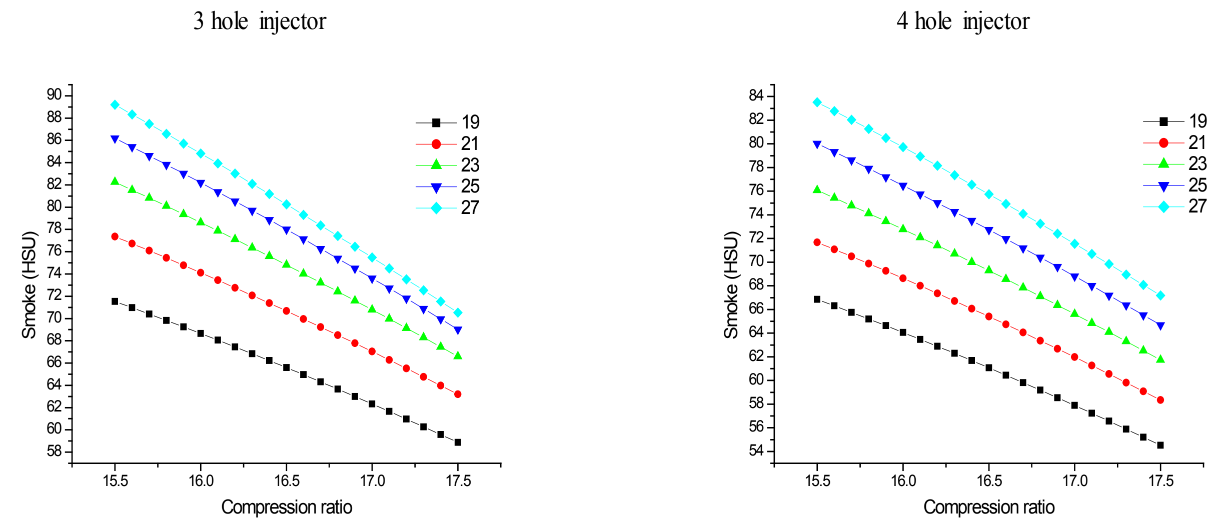

Figure 6: Interaction effect of compression ratio and injection timing on smoke.

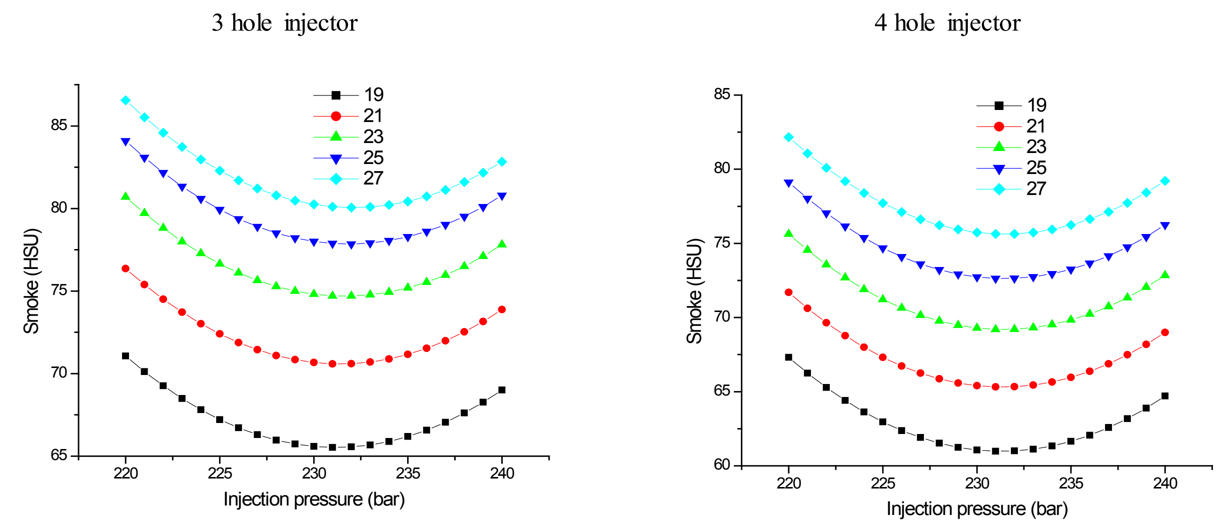

Figure 7: Interaction effect of injection pressure and injection timing on smoke.

charge, hence the HRR during premixed combustion is at the peak level.

Figure 3 presents the behavior of compression ratios with varying IT on BTE for three hole and four hole injectors respectively. In general, the BTE non-linearly with increased compression ratio and with further increase in the IT the BTE tends to decrease. Hence the combination of higher compression ratio with lower IT is desirable for higher BTE. This is because higher compression ratio increases the premixed combustion resulting in higher heat release and hence higher BTE. Under identical conditions of IT and compression ratio, increasing the number of holes from 3 to 4 results in an increased BTE. This could be due to the fine jets of biodiesels emerging from the 4-hole injector ensuring proper mixing of liquid fuel and the surrounding air resulting in improved combustion.

Figure 4 illustrates the variation of BTE due to injection pressure and IT for three hole and four hole injectors respectively. From the figure it can be seen that the BTE increases with the retarded IT for any given value of the injection pressure. Initially, the BTE increases with the increase in injection pressure and beyond 230-bar pressure the BTE decreases for any specified value of the IT and the BTE is found to be maximum for higher values of injection pressure with retarded IT. This could be due to the fact that increase in injection pressure would result in air fuel mixture and hence better combustion. It is revealed from the figure that for the same IT and injection pressure, increasing the number of holes from 3 to 4 results in increased BTE. As mentioned earlier, HOME is more viscous than diesel and hence increased number of holes will ensure proper mixing of the injected fuel with air, which ensures improved fuel combustion process.

Effect of process parameters on the emission characteristics

Smoke: Figure 5 exhibits the estimated smoke density in relation to process parameters, namely, compression ratio and injection pressure.

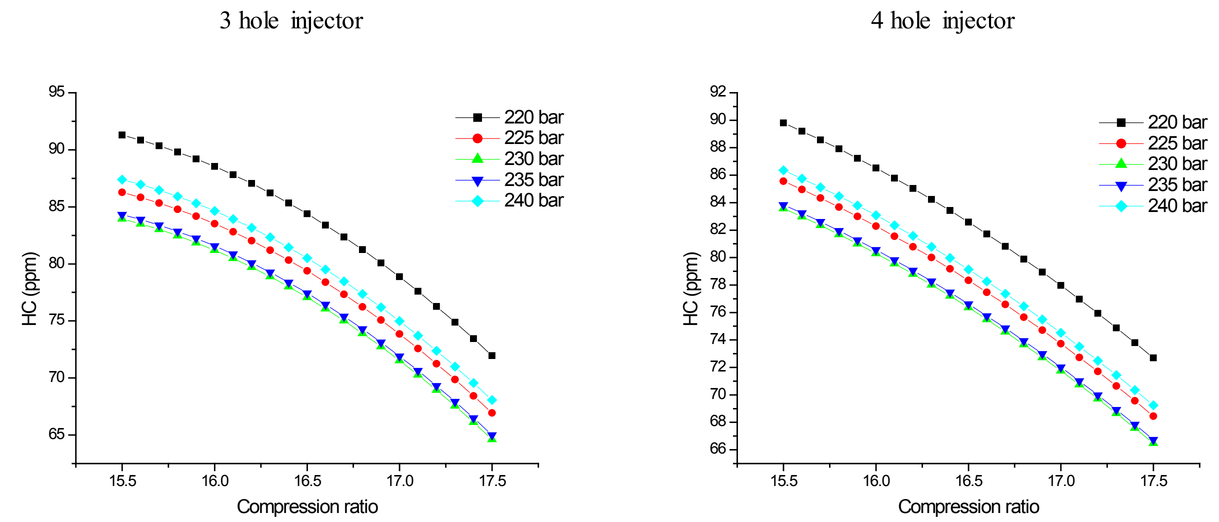

Figure 8: Interaction effect of compression ratio and injection pressure on HC.

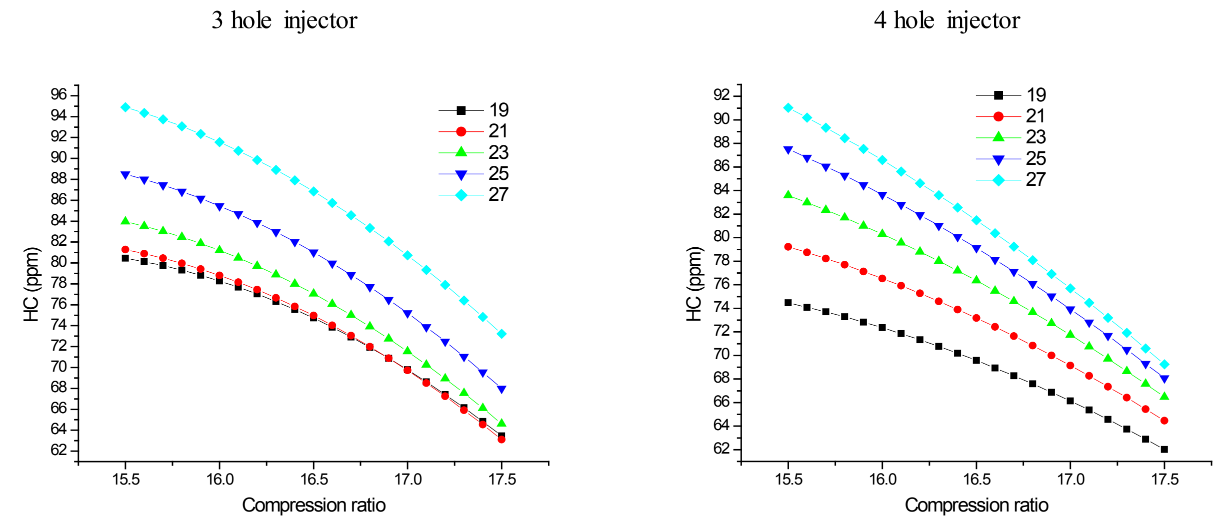

Figure 9: Interaction effect of compression ratio and injection timing on HC.

The smoke density rapidly decreases with increased compression ratio for a particular value of injection pressure and this is because of better atomization; ensuring homogeneous mixing of injected fuel with air [28]. The smoke density is found to be minimum when the compression ratio is 17.5 and the injection pressure is 230 bar for both types of injectors studied. For the same injection pressure and compression ratio, increasing the number of holes from 3 to 4 results in decreased smoke density. The improved mixing of injected liquid fuel and the surrounding air inside the combustion chamber with a 4-hole injector could be the reason for improved combustion performance.

The interaction effects of compression ratio and IT on smoke density are shown in Figure 6 for three hole and four hole injectors. It is observed that, the smoke density sharply decreases with an increase in the compression ratio for any given value of IT and with advanced IT the smoke density increases. Hence it can be inferred that high compression ratio with retarded IT is necessary to reduce smoke density. At retarded ITs, as more time exists for the oxidation process reducing the smoke density. On the other hand, with further increase in the IT, there will be increase in the ignition delay. This may be because; the fuel injection takes place at a lower temperature and pressure in the cylinder. As a result, substantial segment of injected fuel burns during the diffusion phase causing higher smoke density keeping the IT and compression ratio constant and by increasing the number of holes from 3 to 4 results in reduced smoke opacity. Molecular structure of HOME being heavier as compared to diesel needs increased number of nozzle orifices for superior mixing of air and fuel providing near to stoichiometric air-fuel ratio and hence 4 hole injector operation results in reduced smoke opacity.

The behavior of injection pressure and IT on smoke density is represented in Figure 7 for three hole and four hole injectors. For any specified value of the IT, the smoke density decreases with the injection pressure and beyond 230-bar pressure the smoke density decreases. However, with

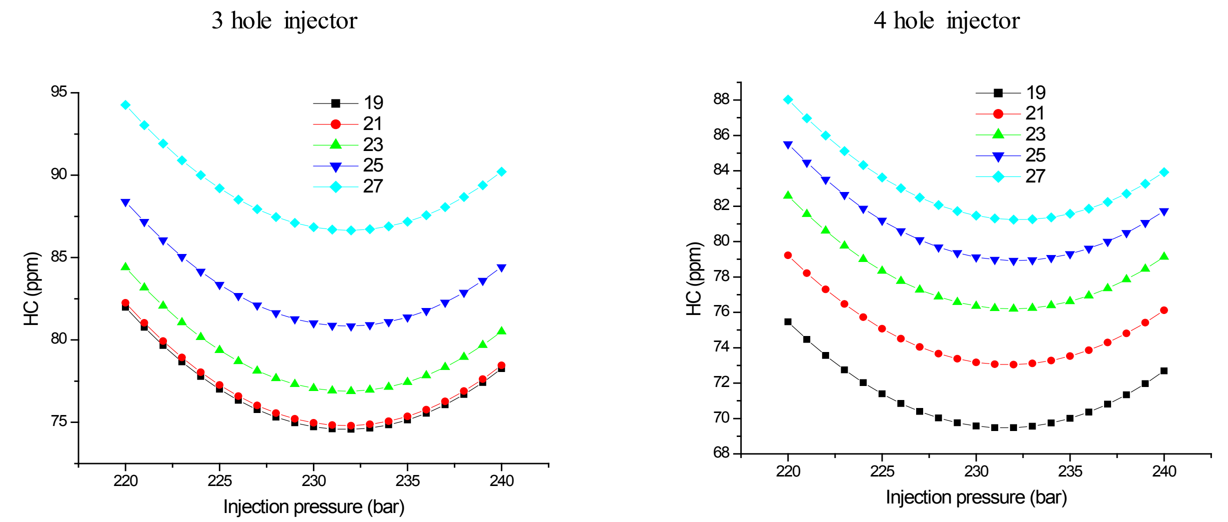

Figure 10: Interaction effect of injection pressure and injection timing on HC.

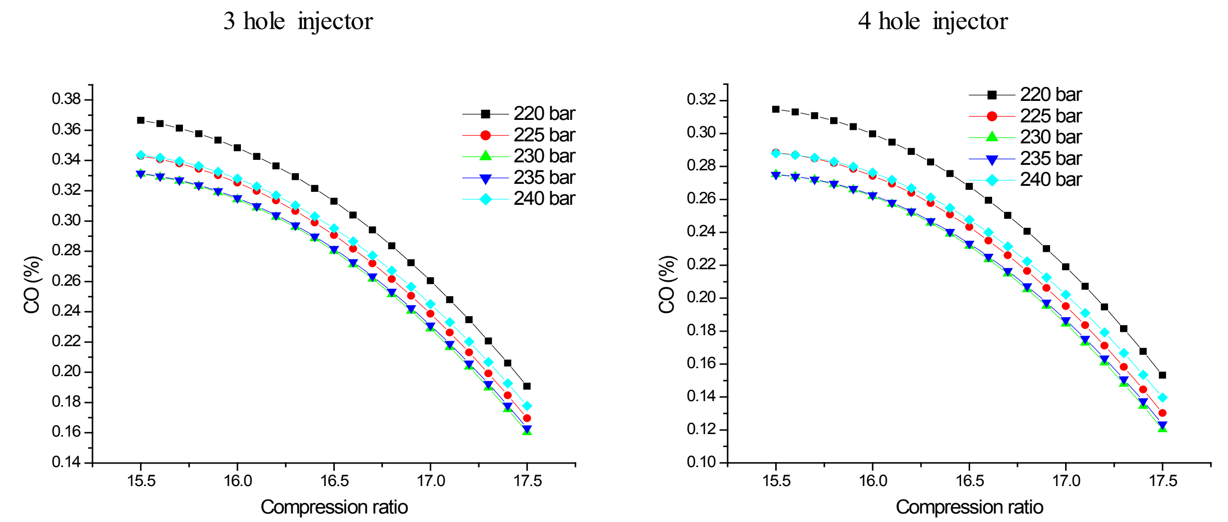

Figure 11: Interaction effect of compression ratio and injection pressure on CO.

advanced timing, the smoke density increases exhibiting similar behavior. The combination of 230 bar injection pressure with 19 degree IT is suitable for reduced smoke density. For the same IT and injection pressure, increasing the number of holes in the injector from 3 to 4 results in reduced smoke opacity.

Hydrocarbon (HC): Figure 8 shows the influence of compression ratio on the HC for different values of injection pressure. From the figure, it can be seen that HC decreases with compression ratio for any specified value of the injection pressure. A combination of 230 bar injection pressure with high compression ratio (17.5) is found to be beneficial for reduced HC. For the same injection pressure and compression ratio, increasing the number of holes in the injector from 3 to 4 resulted in decreased HC. This could be attributed to improved mixing of liquid fuel and the surrounding air inside the combustion chamber with a 4-hole injector and hence resulting in complete combustion. Further, higher BTE at these conditions could be responsible for this observed trend.

Graphic analysis of HC results as a function of compression ratio at various injection timings is given in Figure 9. For a given value of injection timing, HC decreases non-linearly with increased compression ratio and with further increase in the IT the HC tends to increase. It is clearly revealed from the figure that lower IT with a higher compression ratio is vital for lower HC emission. It is worth noting that HC is sensitive to lower values of compression ratio when compared to higher values especially for a 4-hole injector.

Figure 10 depicts the evolution of HC as a function of injection pressure for different values of ITs, which exhibits almost a similar behavior as in the case of smoke density (Figure 7). Hence, it is beneficial to select a combination of 230-bar injection pressure with 19 degree IT for reduced

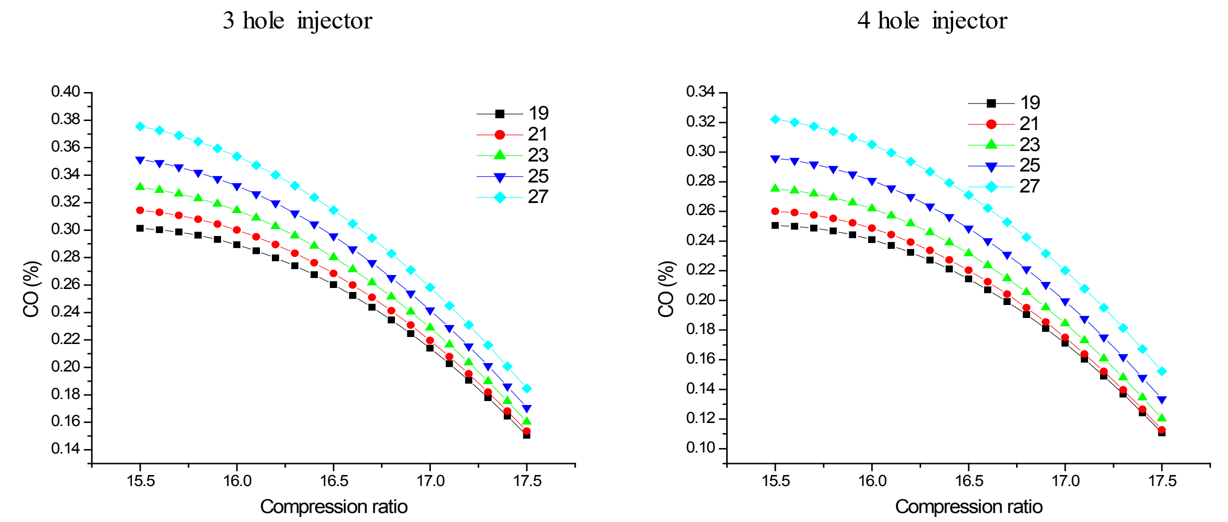

Figure 12: Interaction effect of compression ratio and injection timing on CO.

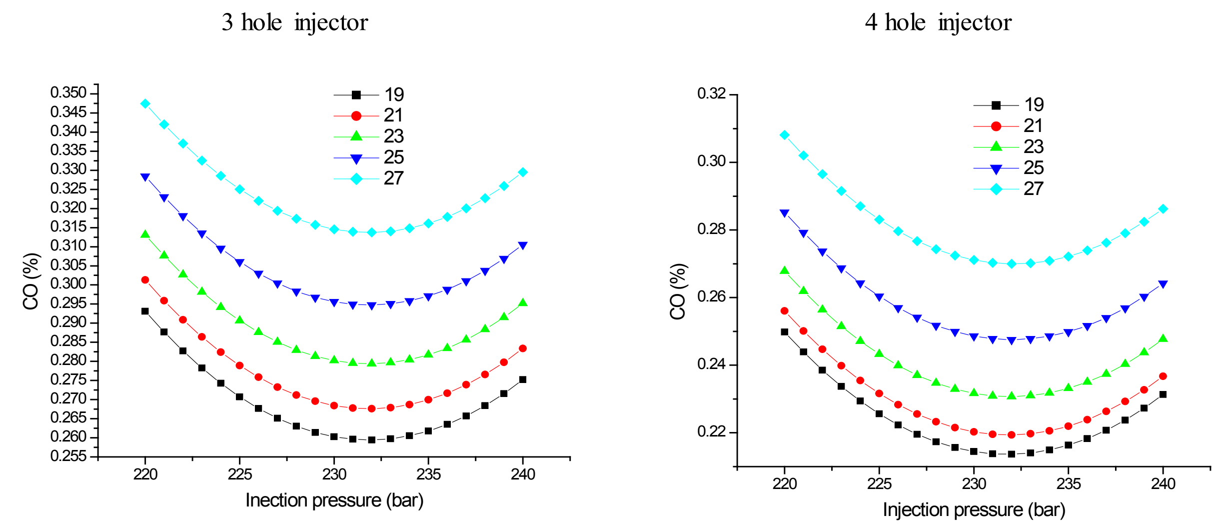

Figure 13: Interaction effect of injection pressure and injection timing on CO.

smoke density in case of both 3 and 4 hole injectors. For the same injection pressure and IT, increasing the number of holes in the injector from 3 to 4 results in a decreased HC.

Carbon monoxide (CO): The interaction effects of compression ratio and injection pressure on CO are demonstrated in the Figure 11. It is observed that, CO decreases with compression ratio for any given value of the injection pressure. However, with further increase in the injection pressure CO decreases. The amount of CO is found to be minimal at a higher value of compression ratio (17.5) and 230-bar injection pressure. As seen from Figure 12, CO also decreases with the compression ratio for a given value of IT but with further increase in the IT the amount of CO increases. It is also revealed from Figure 13 that the behavior of CO in relation to the process parameters (injection pressure and IT) is almost same as that of HC (Figure 10). In all the above cases, increasing the number of holes from 3 to 4 in the injector resulted in decreased CO. The higher HRR accumulated for a 4-hole injector could possibly reduce CO. On the other hand, higher CO region is located near the piston wall for a 3-hole injector because a higher non-homogeneity decreases the combustion efficiency.

Nitric oxide (NO_x): Advanced IT increases the reaction time and consequently the overall gas temperature. Biodiesel fuels having higher cetane number with shorter ignition delay, reduced combustion temperature and residence time are reported to produce lower NO_x formation when used in diesel engines [33]. It was also reported that in order to improve the engine BTE at acceptable NO and soot levels an advanced IT and EGR are necessary [34].

The estimated NOx formation for three hole and four hole injectors is illustrated in Figures 14-16. It is clearly observed from the Figure 14 that

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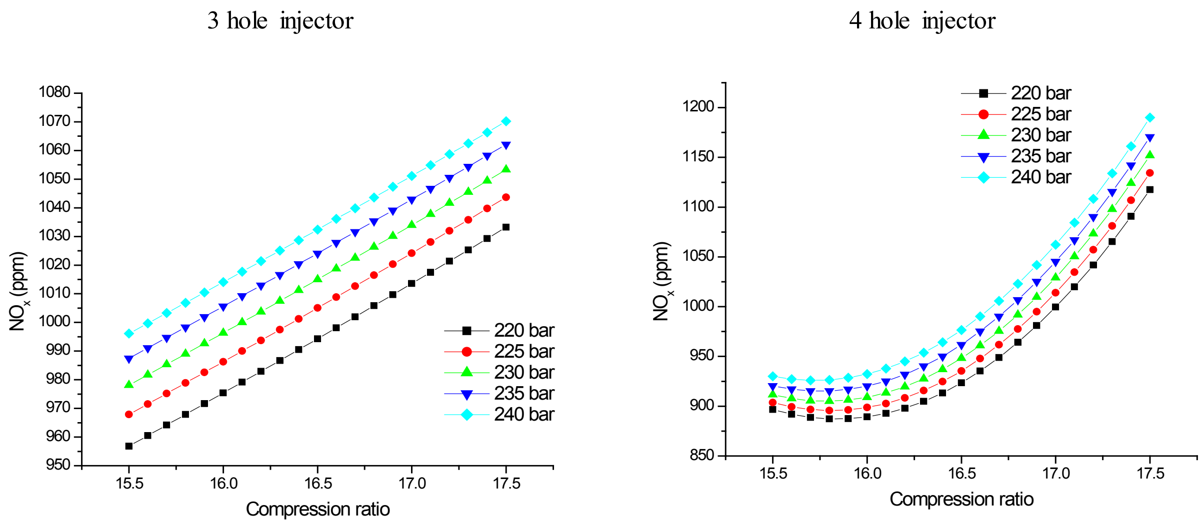

Figure 14: Interaction effect of compression ratio and injection pressure on NO_x.

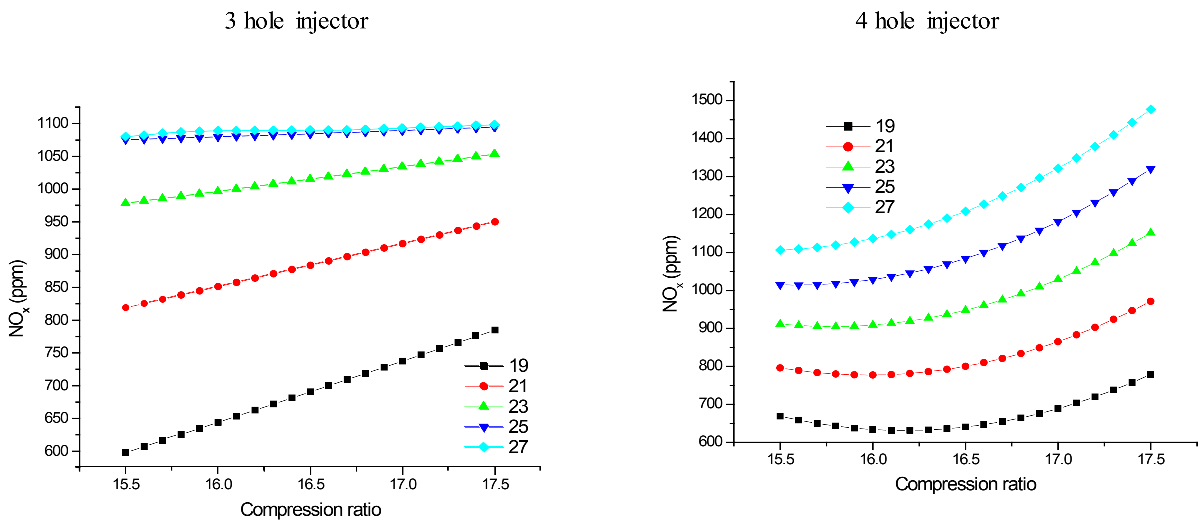

Figure 15: Interaction effect of compression ratio and injection timing on NO_x.

NO_x increases linearly with increased compression ratio for any value of injection pressure and with further increase in injection pressure NO_x also increases for a 3-hole injector. However, it is revealed from the figure that, even though the trend is the same for a 4-hole injector, the behavior of NO_x is found to be non-linear. Figure 15 shows the NO_x behavior in relation to process parameters i.e., compression ratio and IT. It can be seen that, for a 3-hole injector, NO_x linearly increases with the compression ratio at retarded values of ITs (19-23 degree). However, NO_x remains more or less constant for 25 degree IT, while it decreases for higher values of IT. In case of a 4-hole injector in general, NO_x increases with the increase in the compression ratio for a given value of IT and with further advanced IT NO_x increases. But, it is revealed from this figure that NO_x is insensitive to compression ratio. Figure 16 shows the relationship between NO_x and injection pressure at different ITs for 3 hole and 4 hole injectors. However, NO_x increases with advanced IT for both 3 and 4 hole injectors. It is worth mentioning here that, in all the above three cases studied, increasing the number of holes from 3 to 4 resulted in increased NO_x. The probable reason for increased NO_x in case of 4-hole injector might be the higher peak temperature existing inside the combustion chamber [20]. In addition, heat release rate during the premixed combustion stage increases the cylinder temperature causing higher NO_x concentrations.

Bari et al. [29] reported that peak pressure arises at a preceding crank angle achieving higher pressure and therefore higher combustion temperature for advanced ITs. NO_x emission increases with increased injection pressure owing to faster combustion and higher temperature in the process. At higher injection pressures the physical process takes place faster and hence NO_x increase [13]. Higher the injection pressure lower is the ignition delay period, which may be due to the lower Sauter mean diameter (SMD), shorter break up length, higher dispersion and better atomization.

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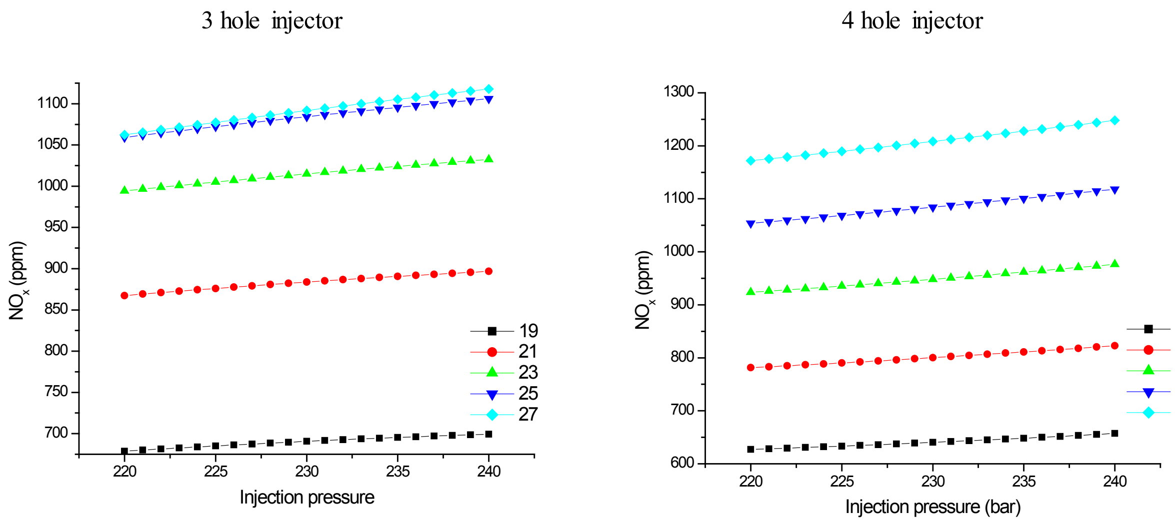

Figure 16: Interaction effect of compression ratio and injection timing on NO_x.

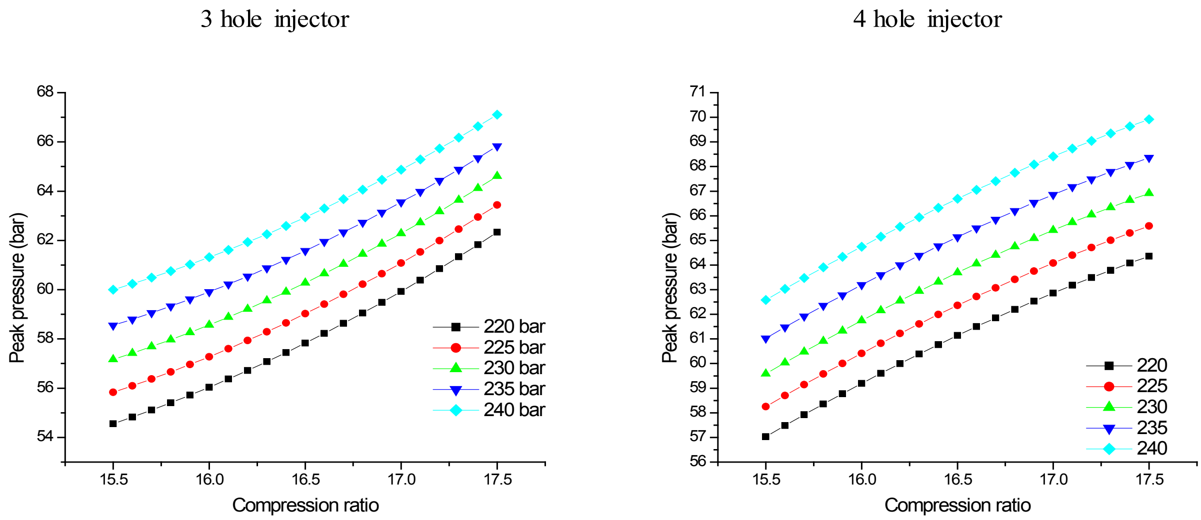

Figure 17: Interaction effect of compression ratio and injection pressure on peak pressure.

Effect of process parameters on the combustion characteristics

Peak pressure: Figure 17 shows the behavior of peak pressure due to compression ratio and injection pressure for 3 and 4 hole injectors. In both the cases the peak pressure increases with the compression ratio for a given value of injection pressure and the peak pressure increases with further increase in the injection pressure. However, the peak pressure is insensitive to compression ratio for both the types of injectors. As can be seen from Figures 18 and 19, the peak pressure exhibits more or less similar trend i.e., the peak pressure increases with increase in the compression ratio and the injection pressure for a specified value of injection timing. However, with the advanced IT the peak pressure decreases. It can be noted from Figures 18 and 19 that a combination of 240-bar injection pressure, compression ratio of 17.5 with 23 degree IT is essential for achieving the maximum peak pressure.

In case of a CI engine, the peak cylinder pressure depends on the burnt fuel fraction throughout the premixed burning phase during the early stages of combustion. The cylinder pressure enhances the ability of the fuel to mix well with air and burn [16]. The rate of pressure rise is the initial derivative of cylinder pressure that relates to the smoothness of the engine operation. The rate of pressure rise increases primarily with the load and then decreases due to the influence of premixed phase at lower loads, whilst the role of the diffusion stage of combustion remains noteworthy at higher loads [35]. Increased injection pressure improves the fuel injection and atomization resulting in improved air fuel mixture and hence elevating the combustion quality [14]. It is obvious that a shorter ignition delay at higher injection pressure advances the combustion resulting in increased peak pressure as well as the HRR. It was reported that higher peak cylinder pressure was observed at an increased compression ratio [22], which also supports our research findings on HOME. Keeping the injection pressure and compression ratio constant and by increasing the number

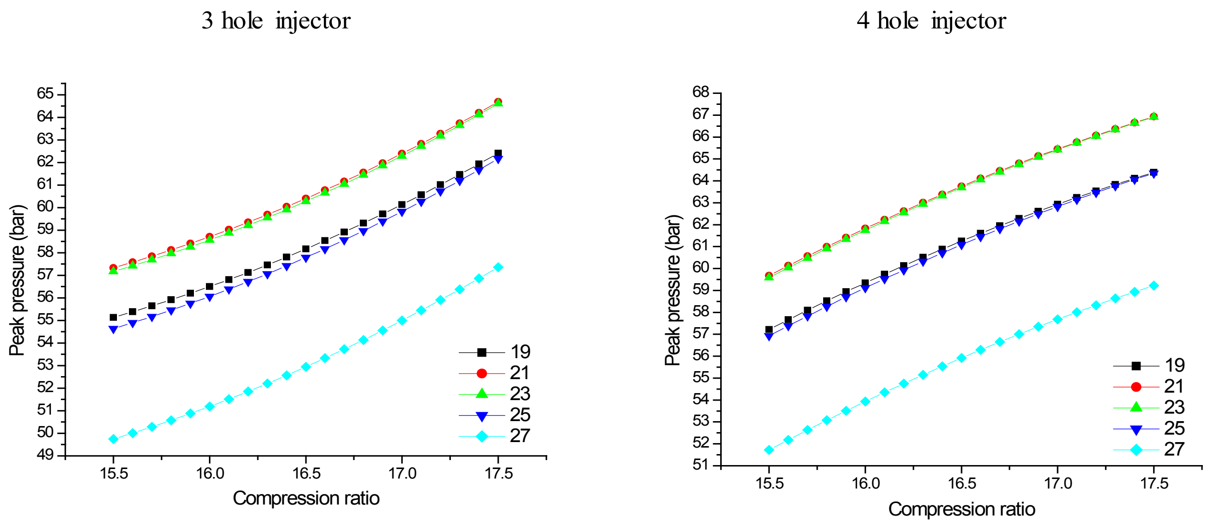

Figure 18: Interaction effect of compression ratio and injection timing on peak pressure.

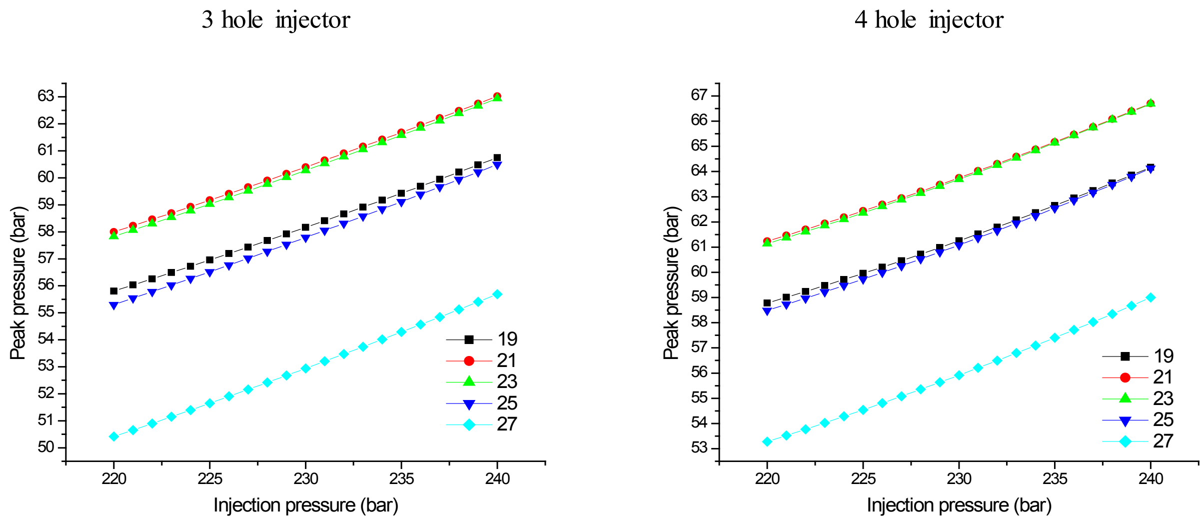

Figure 19: Interaction effect of compression ratio and injection timing on peak pressure.

of holes from 3 to 4 resulted in increased cylinder peak pressure. This could be attributed to better mixing of the injected liquid fuel emerging from the four-hole injector with the surrounding air and thereby providing near stoichiometric air-to fuel ratio inside the combustion chamber [20].

Heat release rate (HRR): The interaction effects of process parameters on HRR are illustrated in Figures 20-22. It is observed that, Figures 20 and 22 clearly exhibit similar behaviors as that of peak pressure (Figures 17 and 19) for both the types of injectors. The behavior of HRR with the compression ratio at different values of ITs (Figure 21) is almost linear for both the injectors i.e., the HRR increases with the compression ratio but the maximum HRR was observed to be achieved with a combination of higher compression ratio (17.5) and medium value of IT (23 degree) for both types of injectors tested.

The amount of heat released during the premixed combustion phase in a CI engine depends on the ignition delay, air fuel mixing rate and the heating value of the fuel. Higher injection pressure improves the atomization as well as air fuel mixing leading to better combustion [13]. With increase in both the IOP and the compression ratio an improvement in heat release characteristics and the reduction in ignition delay were also observed [24]. It has been noted that the premixed combustion will be dominant at the advanced IT as the injection is completed before the combustion begins inside the cylinder. As the number of nozzle holes are increased the heat release rate during the pre-mixed combustion phase and the mixing controlled combustion phase tend to increase [20].

Conclusions

The current study deals with the experimental investigation on performance, emission and combustion characteristics of a single-cylinder

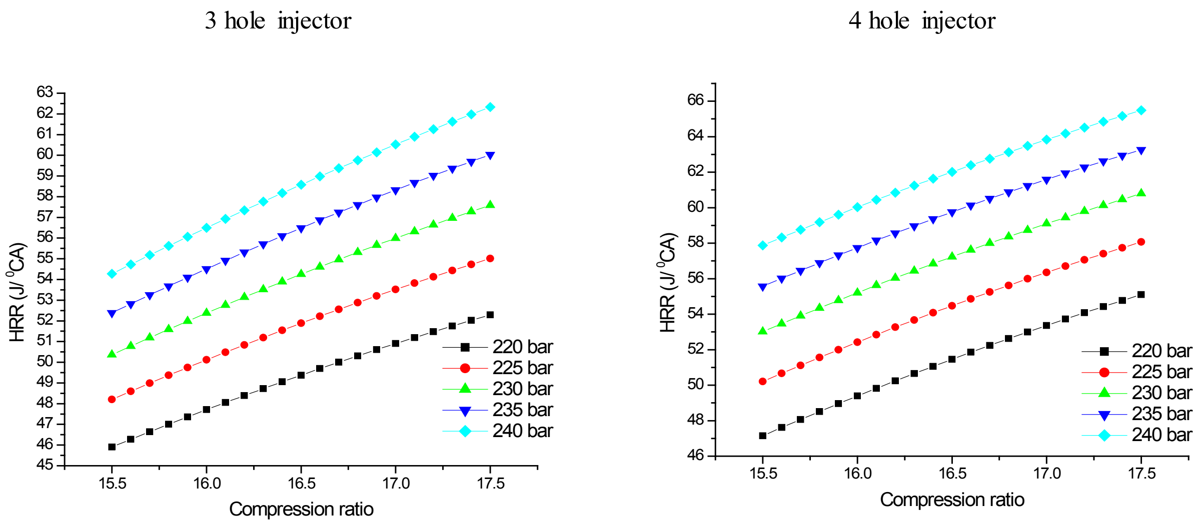

Figure 20: Interaction effect of compression ratio and injection pressure on HRR.

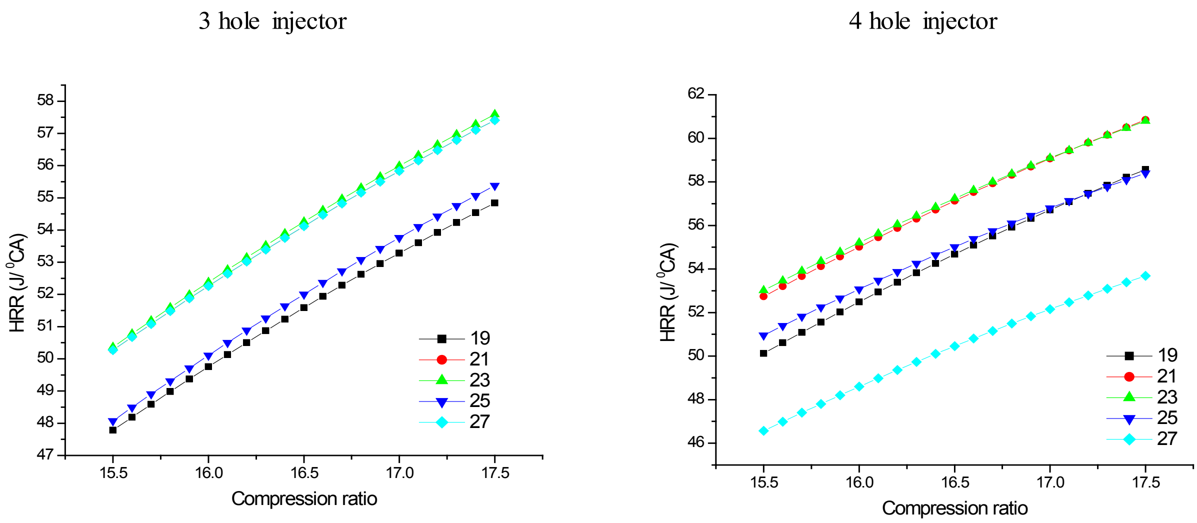

Figure 21: Interaction effect of compression ratio and injection timing on HRR.

direct injection diesel engine when fueled with HOME for 3 and 4 hole injectors using RSM based quadratic models constructed to explore the effects of the three process parameters. The experiments were planned as per the FFD. Based on the experimental results and subsequent response surface analysis, the following conclusion are drawn:

- The BTE increases with increased compression ratio for any given value of injection pressure. Within the injection pressure range of 220-235 bar, increase in the injection pressure results in higher BTE with compression ratio. However, at higher injection pressure level (240 bar), it is observed that the BTE decreases. The investigations indicate that the injection pressure beyond 230 bar results in poor engine performance. The BTE increases with increased injection pressure up to 230-bar pressure and beyond this pressure, the BTE decreases for a given value of IT. The maximum BTE was observed with a combination of higher value of injection pressure and retarded IT.
- The smoke density decreases with increased compression ratio for a specified value of injection pressure. It is minimal when the compression ratio is 17.5 and injection pressure is 230 bar for both the types of injectors (3 and 4 hole). High compression ratio with retarded IT and with a combination of 230 bar injection pressure and 19 degree IT are essential to achieve reduced smoke density.
- HC emission decreases with the compression ratio for any given value of injection pressure. A combination of 230-bar injection pressure, a compression ratio of 17.5 and retarded IT are the essential conditions to obtain reduced HC. The investigations on CO clearly indicate that the pattern of behavior of CO in relation to the identified process parameters (compression ratio, injection pressure and IT) is very similar to that of HC.
- NOx emission increases with increased compression ratio for a given value of IT and with a further advanced IT, NO_x increases.

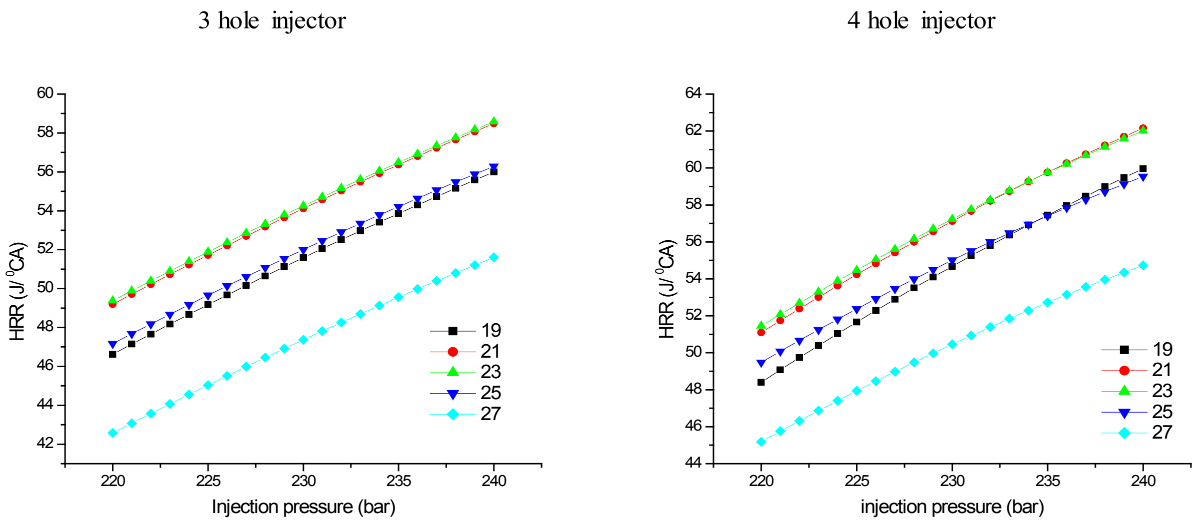

Figure 22: IInteraction effect of injection pressure and injection pressure on HRR.

- The peak pressure increases with the compression ratio for a given value of injection pressure and with a further increased injection pressure the peak pressure increases.
- The HRR increases with the compression ratio but the maximum HRR was observed with a combination of higher compression ratio (17.5) and IT of 23 degree for both types of injectors tested.
- Increasing the number of nozzle holes improves the performance of diesel engine fueled by HOME in terms of increased BTE with reduced CO, HC and smoke emissions and increased NO_x, peak pressure and HRR.

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