Proceedings of 8th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2020 Month: June Volume: 8

Experimental Study on Effect of Number of Nozzle Holes and Hole Axis Angles on Performance and Combustion of Diesel Engine

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Abstract

This research was focused to present the inferences of the experimental studies on the performance and combustion characteristics of diesel fuel for a single-cylinder direct injection diesel engine using response surface methodology (RSM) based mathematical modeling which were developed taking 9 set of experimental results. Experiments were carried out to study the effects of loads and injection pressures on performance characteristics like indicated power (IP), brake thermal efficiency (BTE), specific fuel consumption (SFC), volumetric efficiency (VE), air-fuel ratio (AFR) and combustion characteristics like net heat release (NHR), maximum cylinder pressure (MCP) and mean gas temperature (MGT). The experiments were planned and RSM based quadratic models were developed to establish the relationships between the process parameters and the proposed characteristics using 3 hole, 4 hole (142°and 150°hole axis angle) and 5 hole nozzle. The response surface analysis based on the experimental results revealed that by increasing loads from 2 kg to 10 kg would lead to the increased IP, BTE, NHR, MCP and MGT and decreased SFC, VE and AFR. The better value of BTE, SFC and NHR were obtained from 3 hole nozzle. Increasing the number of nozzle holes improved the combustion characteristics like MCP and MGT. 4 hole nozzle of 142°hole axis angle gave better BTE, VE and MCP and while 4 hole nozzle of 150°hole axis angle improved the IP, SFC, AFR, NHR and MGT.

Keywords

Diesel engine, Combustion characteristics, Performance characteristics, Response surface methodology

1. Introduction

Diesel engines are the primary source of power for the light, medium, and heavy duty applications. The advantages of diesel engines are high fuel efficiency, reliability and durability. The principle operation of Diesel engines depends on the heat within the compressed air to cause an ignition of the fuel charge. The chemical energy stored in the fuel is then converted into mechanical energy, which can be used to power tractors, locomotives, trucks, etc. As no ignition device is employed, it is often called a compression-ignition engine. Nozzle, one of the important part of fuel injection system is truly considered and named as the heart of diesel engine. Nozzle converts the liquid diesel into vapour and which further creates vapour pressure on the piston of the diesel engine and hence converts the linear motion into rotational motion [1] .The efficiency of the diesel engine very much depends on the quality of the nozzle. Actually, diesel injector nozzles have a significant influence on the quality of spray and preparation of air–fuel mixture [4] . It regulates the flow of fuel to the ultimate ignition compartment. The main purpose of the Fuel Injection Nozzle is to direct and atomize the metered fuel into the combustion chamber.

This paper discusses the effect of number of nozzle holes on the performance and combustion characteristics of a single cylinder direct injection diesel engine fueled with diesel for different injection pressures and loads. RSM based mathematical modeling using design of experiments (DOE) is found to be a capable modeling tool [2] . The RSM is not only useful in reducing the cost and time but also furnishing the decisive information about the interaction effects of factors [3]. Hence, an effort has been made in the research work to build the RSM based quadratic models of performance and combustion characteristics. The effects of load and injection pressure on performance characteristic like IP, BTE, SFC, VE and AFR and combustion characteristics like NHR, MCP and MGT have been analyzed for 3 hole, 4 hole (142°), 4 hole (150°) and 5 hole nozzle by developing second order RSM based mathematical models.

1.1 Research Objectives

The main objective was to carry out experimental investigation and mathematical modeling on effect of number of nozzle holes and hole axis angles on performance and combustion of diesel engine.

The specific objectives were:

- To find the performance characteristics like IP, BTE, SFC, VE, AFR and combustion characteristics like NHR, MCP and MGT using 3 holes, 4 holes and 5 holes nozzle.
- To study the effect of different hole axis angles of 4 hole nozzle like 142°and 150°on performance and combustion of diesel engine.
- To employ the response surface methodology (RSM) based mathematical modeling for effective analysis of results.
- To use design expert software for RSM based modeling and their statistical testing.

2. Experimental Setup

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 661 cc, compression ratio of 17.5:1 and developing 5.2 kW power at 1500 rpm. The engine is equipped with a traditional fuel injection system, which was operated at a rated speed of 1500 rpm throughout the experimentation period. Eddy current dynamometer was used for loading the engine. The injection pressure of the injector was manipulated for research tests.The setup consisted of labview based engine performance analysis software package "Enginesoft" which were used for on line engine performance evaluation.

Figure 1: Fuel injector nozzles

The experiment was carried out for three different nozzle configurations of 3 hole (DLLA110S639), 4 hole nozzle of 142°hole axis angle (DLLA142S1142), 4 hole nozzle of 150°hole axis angle (DLLA150S187) and five hole (DLLA158S769) nozzle to study its effect on the performance and combustion of diesel engine. Variation of load from 2 kg to 10 kg was only taken as a sample for experimental investigation. However, 4 stroke single cylinder diesel engine can be used for generators, pumps and other light vehicles. The nozzles used in the experiment and the experimental setup are shown in figures 1 and 2 respectively.

Figure 2: Experimental Setup

3. Mathematical Modeling

In the thesis work, each controllable parameter was investigated at three levels to explore the non-linearity effects and hence, second order RSM based mathematical models for IP, BTE, SFC, VE, AFR, NHR, MCP, MGT, etc. had been constructed with injection pressure (P) and load (L) as the process parameters. The quadratic mathematical model is of the form [3]:

$$Y = b_0 + b_1 L + b_2 P + b_{11} L^2 + b_{22} P^2 + b_{12} LP \quad (1)$$

where, Y: response, i.e., BTE, SFC, VE, NHR, MCP, MGT, etc.; b0,........,b12 : regression coefficients of models are to be determined for each of the responses. The regression coefficients of the proposed models are calculated as [3]:

$$B = (X^T X)^{-1} X^T Y \quad (2)$$

where, B: matrix of parameter estimates; X: calculation matrix, which includes linear, quadratic and interaction terms, XT: transpose of X and Y: matrix of response. Design expert version 12 software was used for the calculation of RSM based mathematical models.

Table 1: Parameters and their levels

Parameters	Levels		
Injection pressure (P), bar	210	220	230
Loads (L), Kg	2	6	10

Table 2: Experimental layout plan

Trial no.	Injection pressure	loads
1.	210	2
2.	210	6
3.	210	10
4.	220	2
5.	220	6
6.	220	10
7.	230	2
8.	230	6
9.	230	10

Table 3: Measured Values of performance and combustion characteristics of 3 hole nozzle

Trial no.	IP (kw)	BTE (%)	SFC (kg/kwh)	VE (%)	AFR	NHR (J/deg)	MCP (bar)	MGT (°C)
1.	1.992	11.186	1.463	81.769	66.064	20.566	47.033	871.868
2.	3.064	21.719	0.402	81.196	42.001	33.974	54.638	1009.67
3.	3.813	28.653	0.274	80.371	33.384	46.586	61.947	1131.13
4.	1.992	11.207	1.909	81.722	50.789	21.989	47.423	878.302
5.	3.064	23.368	0.576	80.844	37.817	33.755	55.174	1012.01
6.	3.813	28.297	0.293	80.371	30.485	50.583	62.849	1142.79
7.	2.057	9.748	1.322	81.941	58.506	22.484	48.293	876.373
8.	3.009	21.354	0.424	81.403	41.453	36.536	58.318	1067.85
9.	3.953	26.126	0.307	80.323	30.015	53.084	62.687	1135.64

Table 4: Measured Values of performance and combustion characteristics of 4 hole nozzle (142º)

Trial no.	IP (kw)	BTE (%)	SFC (kg/kwh)	VE (%)	AFR	NHR (J/deg)	MCP (bar)	MGT (°C)
1.	1.723	9.831	1.072	81.626	59.279	20.979	47.368	857.683
2.	2.595	21.52	0.401	81.275	41.702	33.053	53.885	968.946
3.	3.583	23.431	0.353	80.219	26.811	47.905	61.258	1102.61
4.	1.775	9.97	1.111	81.026	59.010	21.979	47.791	857.542
5.	2.649	20.989	0.425	81.080	40.505	34.742	54.354	970.138
6.	3.41	23.371	0.361	80.040	27.034	46.792	60.279	1081.97
7.	1.733	9.845	1.115	81.269	58.487	22.422	48.055	861.836
8.	2.848	20.225	0.420	80.762	38.905	28.647	56.39	980.115
9.	3.712	22.395	0.373	79.32	25.606	40.36	62.805	1122.8

Table 5: Measured Values of performance and combustion characteristics of 4 hole nozzle (150º)

Trial no.	IP (kw)	BTE (%)	SFC (kg/kwh)	VE (%)	AFR	NHR (J/deg)	MCP (bar)	MGT (°C)
1.	2.190	9.79	1.305	82.167	57.274	21.999	49.032	886.677
2.	3.038	19.894	0.452	81.617	38.669	32.788	54.632	990.177
3.	4.148	23.014	0.359	80.688	26.611	48.384	62.502	1143.28
4.	2.320	8.739	1.662	82.485	52.981	22.012	49.429	921.864
5.	3.345	20.307	0.417	81.835	39.579	37.86	57.153	1028.12
6.	4.126	21.500	0.370	80.729	24.593	47.696	62.931	1133.42
7.	2.137	9.153	1.297	82.311	54.215	20.977	48.843	879.362
8.	3.305	16.611	0.528	81.710	32.297	38.806	57.321	1026.97
9.	3.995	18.876	0.441	80.618	22.039	45.303	62.223	1130.82

Table 6: Measured Values of performance and combustion characteristics of 5 hole nozzle

Trial no.	IP (kw)	BTE (%)	SFC (kg/kwh)	VE (%)	AFR	NHR (J/deg)	MCP (bar)	MGT (°C)
1.	2.192	10.886	1.136	82.244	65.84	26.9	51.158	910.459
2.	2.907	22.820	0.389	81.275	44.26	38.63	57.273	1008.41
3.	3.864	26.361	0.318	80.231	30.277	55.049	64.655	1149.29
4.	1.676	11.231	1.033	81.506	66.343	26.055	49.603	876.064
5.	2.677	20.503	0.404	80.668	39.496	45.053	58.495	1022.36
6.	3.486	26.531	0.313	79.806	30.506	52.514	64.024	1125.59
7.	1.677	10.957	1.092	81.309	65.966	25.456	49.213	869.966
8.	2.518	23.076	0.373	80.962	44.559	38.08	57.089	1007.89
9.	3.484	26.015	0.323	79.812	29.616	56.656	64.558	1133.87

Three hole nozzle equations:

$IP = 13.56800 + 0.209375*L - 0.110313*P - 0.006812*L^2 + 0.000250*P^2 + 0.000469*L*P$

$BTE = - 550.82426 + 5.82779*L + 5.07120*P - 0.184010*L^2 - 0.011597*P^2 - 0.006806*L*P$

$SFC = - 105.66811 - 0.743917*L + 0.992308*P + 0.028792*L^2 - 0.002273*P^2 + 0.001087*L*P$

$VE = 170.01210 + 0.169167*L - 0.814167*P - 0.004052*L^2 + 0.001882*P^2 - 0.001375*L*P$

$AFR = 2825.18676 - 12.49229*L - 24.72507*P + 0.278135*L^2 + 0.055402*P^2 + 0.026181*L*P$

$NHR = 59.91958 - 3.59217*L - 0.411183*P + 0.070437*L^2 + 0.000960*P^2 + 0.028625*L*P$

$MCP = 180.52711 + 3.33242*L - 1.37010*P - 0.062792*L^2 + 0.003373*P^2 - 0.003250*L*P$

$MGT = 2654.99425 + 50.49087*L - 18.18741*P - 1.48912*L^2 + 0.043880*P^2 + 0.000019*L*P$

Four hole nozzle of 142º hole axis angle equations:

$$IP = 43.15247 + 0.095458*L - 0.383663*P - 0.002583*L^2 + 0.000877*P^2 + 0.000744*L*P$$

$$BTE = - 112.95263 + 6.41983*L + 1.03696*P - 0.277344*L^2 - 0.002355*P^2 - 0.006563*L*P$$

$$SFC = -3.64579 - 0.297125*L + 0.046229*P + 0.019719*L^2 - 0.000100*P^2 - 0.000144*L*P$$

$$VE = 97.53353 + 0.906083*L - 0.140425*P - 0.028479*L^2 + 0.000298*P^2 - 0.003388*L*P$$

$$AFR = - 101.79843 - 5.23771*L + 1.62812*P + 0.145865*L^2 - 0.003847*P^2 - 0.002581*L*P$$

$$NHR = - 1118.45010 + 14.31758*L + 10.17925*P + 0.078677*L^2 - 0.022767*P^2 - 0.056175*L*P$$

$$MCP = 429.44419 + 0.743917*L - 3.55613*P - 0.017729*L^2 + 0.008188*P^2 + 0.005375*L*P$$

$$MGT = 6827.42389 + 2.62467*L - 54.79023*P + 0.479667*L^2 + 0.124502*P^2 + 0.100225*L*$$

Four hole nozzle of 150º hole axis angle equations:

$$IP = - 61.34456 + 0.429250*L + 0.568700*P - 0.004792*L^2 - 0.001282*P^2 - 0.000625*L*P$$

$$BTE = -300.18947 + 9.12071*L + 2.74992*P - 0.234917*L^2 - 0.006257*P^2 - 0.021881*L*P$$

$$SFC = - 39.14500 - 0.582667*L + 0.377525*P + 0.027500*L^2 - 0.000860*P^2 + 0.000562*L*P$$

$$VE = 0.569250 + 0.254667*L + 0.734608*P - 0.013812*L^2 - 0.001645*P^2 - 0.001338*L*P$$

$$AFR = - 153.10754 - 3.79862*L + 2.17075*P + 0.173156*L^2 - 0.005335*P^2 - 0.009456*L*P$$

$$NHR = - 565.46554 + 7.58137*L + 5.15373*P - 0.130594*L^2 - 0.011465*P^2 - 0.012869*L*P$$

$$MCP = - 324.15000 + 2.21158*L + 3.32059*P - 0.033875*L^2 - 0.007455*P^2 - 0.000563*L*P$$

$$MGT = - 8090.11108 + 36.44754*L + 80.78977*P + 0.050875*L^2 - 0.182530*P^2 - 0.032156*L*P$$

Five hole nozzle equations:

$$IP = 84.92135 + 0.012875*L - 0.733396*P + 0.001823*L^2 + 0.001607*P^2 + 0.000844*L*P$$

$$BTE = 288.28946 + 5.08521*L -2.61368*P - 0.216844*L^2 + 0.005975*P^2 - 0.002606*L*P$$

$$SFC = 12.83024 -0.398875*L - 0.098821*P + 0.019615*L^2 + 0.000218*P^2 + 0.000306*L*P$$

$$VE = 243.18247 - 0.813833*L - 1.42067*P - 0.009396*L^2 + 0.003122*P^2 + 0.003225*L*P$$

$$AFR = 706.63989 - 7.39721*L -5.71495*P + 0.332479*L^2 + 0.013047*P^2 - 0.004919*L*P$$

$$NHR = - 476.04669 - 0.507792*L + 4.62600*P -0.009333*L^2 - 0.010788*P^2 + 0.019069*L*P$$

$$MCP = 45.26707 - 0.425500*L + 0.112133*P - 0.026073*L^2 - 0.000497*P^2 + 0.011550*L*P$$

$$MGT = 3798.86829 - 1.61838*L - 25.22939*P - 0.126094*L^2 + 0.053065*P^2 + 0.156706*L*P$$

4. Statistical Testing

The statistical testing of the developed quadratic mathematical models were tested through F-test for the analysis of variance (ANOVA) [4]. 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. Using Design Expert 12 Table 7 to table 10 were constructed which represented the ANOVA results of the developed models and found to be significant at 95% confidence interval as F-ratio of all the models is greater than 9.01 (F- table (5, 3, 0.05)). The adequacy of the models was also verified through P-values where the values less than 0.0500 indicate the model terms are significant and coefficient of determination R^2 [3] that provides a measure of variability in the observed values of the response and can be explained by the parameters and their interactions. R^2 values given in the table were obtained closer to unity and this showed a good correlation between the experimental and the predicted values of the proposed characteristics. Hence, these quadratic models are used to predict the characteristics by substituting the values of load and injection pressure within the ranges of the process parameters selected. Formulas used for statistical testing were:

F-test for ANOVA = Mean squares for Regression / Mean squares for Residual

R^2 = Model sum of squares / Total sum of squares

Table 7: ANOVA results for Quadratic Model and R^2 values of 3 hole nozzle

S.N	Charac-teristics	Sum of squares		Degree of freedom		Mean squares		F-ratio	P - value	R^2
		Regression	Residual	Regression	Residual	Regression	Residual			
1.	IP	5.14	0.0115	5	3	1.03	0.0038	268.41	0.0004	0.9978
2.	BTE	455.84	1.33	5	3	91.17	0.4443	205.21	0.0005	0.9971
3.	SFC	2.97	0.0941	5	3	0.5937	0.0314	18.92	0.0178	0.9693
4.	VE	3.29	0.0867	5	3	0.6576	0.0289	22.76	0.0137	0.9743
5.	AFR	1233.69	45.95	5	3	246.74	15.32	16.11	0.0224	0.9641
6.	NHR	1238.13	2.90	5	3	247.63	0.9671	256.06	0.0004	0.9977
7.	MCP	341.21	3.53	5	3	68.24	1.18	58.04	0.0035	0.9898
8.	MGT	1.041E + 05	1469.40	5	3	20822.20	489.80	42.51	0.0055	0.9861

Table 8: ANOVA results for Quadratic Model and R^2 values of 4 hole nozzle (142°)

S.N	Charac-teristics	Sum of squares		Degree of freedom		Mean squares		F-ratio	P -value	R^2
		Regression	Residual	Regression	Residual	Regression	Residual			
1.	IP	5.04	0.0384	5	3	1.01	0.0128	78.71	0.0022	0.9924
2.	BTE	301.38	0.2545	5	3	60.28	0.0848	710.60	<0.0001	0.9992
3.	SFC	1.02	0.0002	5	3	0.2031	0.0001	3059.89	<0.0001	0.9998
4.	VE	4.15	0.1724	5	3	0.8308	0.0575	14.46	0.0260	0.9602
5.	AFR	1593.76	1.27	5	3	318.75	0.4248	750.36	<0.0001	0.9992
6.	NHR	861.28	5.11	5	3	172.26	1.70	101.11	0.0015	0.9941
7.	MCP	287.35	1.76	5	3	57.47	0.5874	97.84	0.0016	0.9939
8.	MGT	89597.80	336.45	5	3	17919.56	112.15	159.78	0.0008	0.9963

Table 9: ANOVA results for Quadratic Model and R^2 values of 4 hole nozzle (150°)

S.N	Charact-eristics	Sum of squares		Degree of freedom		Mean squares		F-ratio	P - value	R^2
		Regression	Residual	Regression	Residual	Regression	Residual			
1.	IP	5.32	0.0512	5	3	1.06	0.0171	62.34	0.0031	0.9905
2.	BTE	255.43	2.86	5	3	51.09	0.9538	53.56	0.0039	0.9889
3.	SFC	2.00	0.0767	5	3	0.4006	0.0256	15.66	0.0233	0.9631
4.	VE	4.22	0.0107	5	3	0.8431	0.0036	235.77	0.0004	0.9975
5.	AFR	1436.23	17.93	5	3	287.25	5.98	48.05	0.0046	0.9877
6.	NHR	985.73	22.58	5	3	197.15	7.53	26.19	0.0112	0.9776
7.	MCP	273.90	3.04	5	3	54.78	1.01	54.14	0.0039	0.9890
8.	MGT	87028.50	1329.39	5	3	17405.70	443.13	39.28	0.0062	0.9850

Table 10: ANOVA results for Quadratic Model and R^2 values of 5 hole nozzle

S.N	Chara-cteristics	Sum of squares		Degree of freedom		Mean squares		F-ratio	P - value	R^2
		Regression	Residual	Regression	Residual	Regression	Residual			
1.	IP	4.99	0.0185	5	3	0.9990	0.0062	162.31	0.0008	0.9963
2.	BTE	374.94	3.47	5	3	74.99	1.16	64.92	0.0030	0.9908
3.	SFC	1.09	0.0038	5	3	0.2172	0.0013	170.82	0.0007	0.9965
4.	VE	5.29	0.0643	5	3	1.06	0.0214	49.39	0.0044	0.9880
5.	AFR	1995.18	13.14	5	3	399.04	4.38	91.14	0.0018	0.9935
6.	NHR	1231.89	35.15	5	3	246.38	11.72	21.03	0.0153	0.9723
7.	MCP	313.98	1.83	5	3	62.80	0.6107	102.83	0.0015	0.9942
8.	MGT	95066.50	633.01	5	3	19013.30	211.00	90.11	0.0018	0.9934

5. Graphical Analysis

The data obtained from the experiment were graphically analyzed. The effects of process parameters on performance characteristics for 3 hole, 4 hole 142 degree, 4 hole 150 degree and 5 hole nozzles are presented in figures 3 to 10. These plots were generated considering two parameters namely, injection pressure and load at a time.

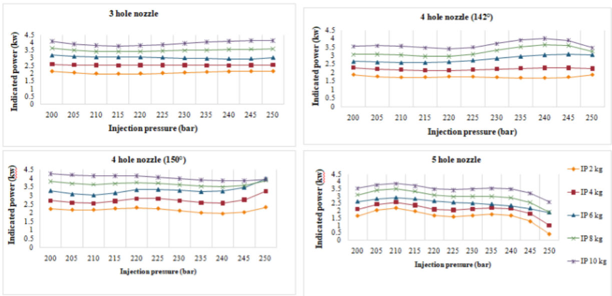

Figure 3: Interaction effect of injection pressure and load on indicated power for nozzles of different holes

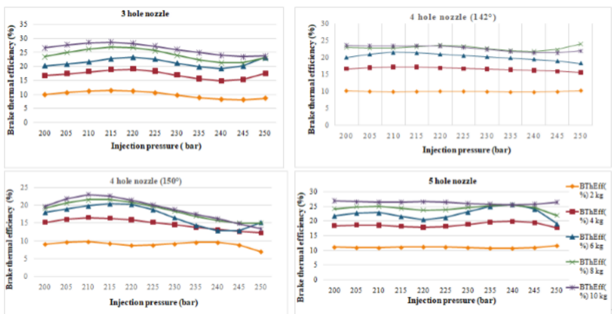

Figure 4: Interaction effect of injection pressure and load on brake thermal efficiency for nozzles of different holes

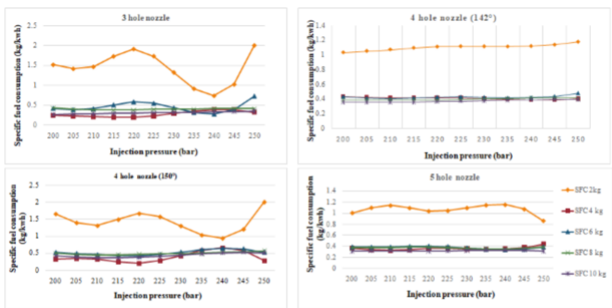

Figure 5: Interaction effect of injection pressure and load on specific fuel consumption for nozzles of different holes

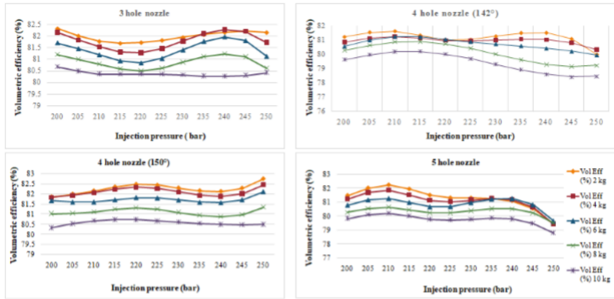

Figure 6: Interaction effect of injection pressure and load on volumetric efficiency for nozzles of different holes

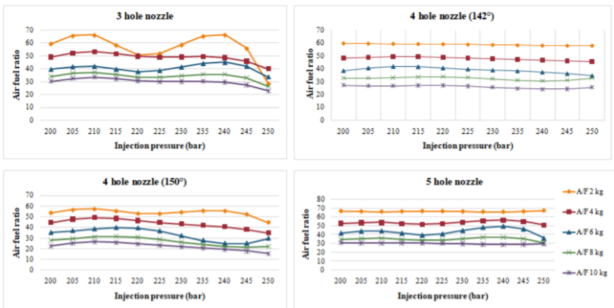

Figure 7: Interaction effect of injection pressure and load on air fuel ratio for nozzles of different holes

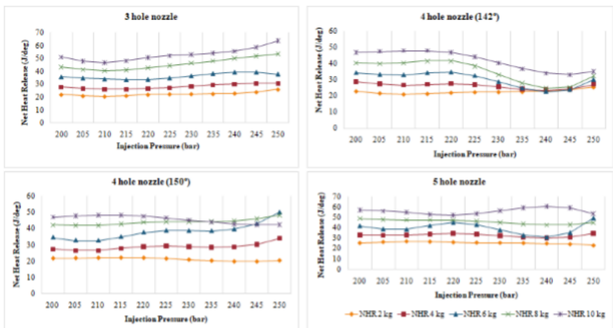

Figure 8: Interaction effect of injection pressure and load on net heat release for nozzles of different holes

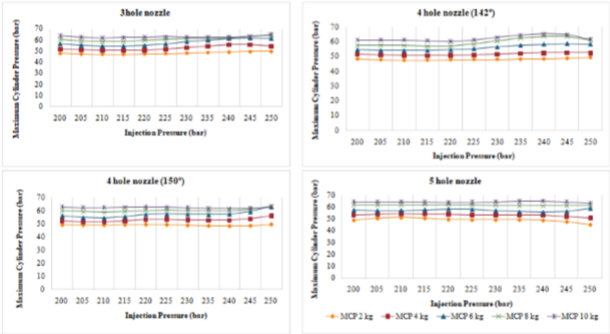

Figure 9: Interaction effect of injection pressure and load on maximum cylinder pressure for nozzles of different holes

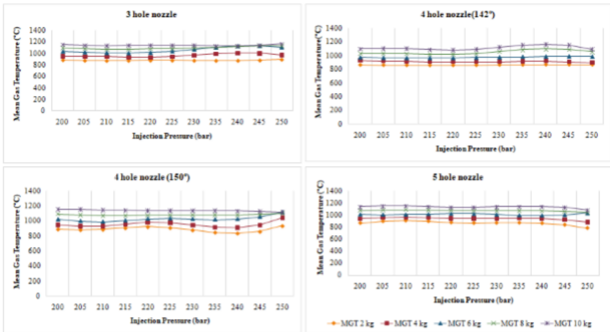

Figure 10: Interaction effect of injection pressure and load on mean gas temperature for nozzles of different holes

Indicated Power (IP):
The interaction effects of injection pressure and load on indicated power for 3, 4 (142°and 150°) and 5 hole nozzles are shown in figure 3. Indicated power is the amount of power developed in the cylinder by the combustion of fuel and can be considered as the power exerted on the piston. Generally, high indicated power is preferred for diesel engine. From the figure 3, it is clear that indicated power increases with the increase of load for all 3 hole, 4 (142°and 150°) hole and 5 hole injector nozzles. The maximum IP obtained was 4.12 kw at 245 bar at 10 kg for 3 hole nozzle. From the graphs of 4 hole (142°), it was clear that IP increases with the increase of injection pressure (in the range of 220 to 245 bar) for loads of 6 kg, 8kg and 10 kg. The hole axis angle of 142º gave the maximum IP of 4.01 kw at 245 bar at 10 kg load. In the graphs of 4 hole (150°), it was found that IP increases from 210 to 220 bar and again IP decreases with further increase in injection pressure till 240 bar. The hole axis angle of 150º gave the highest IP of 4.25 kw at 200 bar at 10 kg. Graph of 5 hole nozzle showed different behavior compared to the other hole nozzle injectors. Though IP increased with increase in load but the value of IP went on decreasing with increase of injection pressure from (210 to 230) bar. 3.86 kw was the higher value of IP that was obtained at 210 bar at 10 kg load for 5 hole nozzle.

Brake Thermal efficiency (BTE):
BTE is brake power of a heat engine as a function of thermal input from the fuel. It is used to evaluate how well an engine converts the heat from a fuel to mechanical energy. Graphs in the figure 4 exhibit brake thermal efficiency in relation to load and injection pressure for different nozzles. It is observed that, for any specified value of injection pressure, the BTE increased with the increase in load. Graph of 3 hole nozzle gave higher BTE at 220 bar pressure which is largely due to the improved atomization, spray characteristics and air-fuel mixing which results in better combustion. For the 3 hole injector, the highest BTE of 28.653 % was achieved at 210 bar for 10 kg load. The highest BTE achieved for 4 hole injector of 142 degree hole axis angle was 23.431 % at 210 bar for 10 kg load. It is revealed from the graph that, increase in injection pressure leads to decrease in BTE because high injection pressure may be responsible to higher velocity of droplet which will pass away without mixing air properly and thus lower BTE due to improper combustion. The behavior of BTE graphs for 4 hole nozzle of 150°hole axis angle was different compared to 4 hole injector of 142°hole axis angle. Graph of 5 hole injector illustrated that the highest BTE obtained was 26.53 % for 10 kg load at 220 bar.

Specific Fuel Consumption (SFC):
SFC measures how efficiently an engine is using fuel to produce power. Lower specific fuel consumption is desirable for the diesel engine. All the four graphs in the figure 5 for SFC presented that for any specified value of injection pressure, SFC decreases with increase in load. Graphs of 3 hole nozzle showed that lowest SFC obtained was 0.196 kg/kwh at 215 bar for 4 kg load.SFC increases and decreases for 3 hole nozzle at 2 kg load because at this lower load the actual combustion process was incomplete as enough air was not present in the cylinder to oxidize the fuel completely. Graph of 4 hole injector of 142°hole axis angle represented that SFC increases with the increase in injection pressure. This could be due to the fact that with increase in injection pressure, not only the fuel droplet size decreases but also increases the

momentum of the droplets. Therefore, too high increase in pressures would have developed even small droplets but with increase in momentum the droplets could have got impinged on the cylinder inner wall and to develop same power, the fuel consumption should have increased. Therefore, effect of increasing injection pressure increases the SFC. Graph of 4 hole injector 150 °hole axis angle represented the similar nature of graphs for SFC as that of 3 hole nozzle. The lowest SFC is 0.199 kg/kwh at 200 bar for 10 kg load. Graph of 5 hole injector showed opposite nature of graph compared to 3 hole nozzle. Thus, at the prevailing conditions, an injection pressure of 220 bar yielded lower SFC. Rohit Sharma et. al, 2013 on similar study found out that the same result of increase in SFC with the increase in injection pressure [5].Lowest SFC achieved was 0.308 kg/kwh at 200 bar for 10 kg load. It is also clear from the graphs that for same injection pressure and load, increasing number of nozzle holes from 3 to 5 resulted in increased SFC.

Volumetric Efficiency (VE):

Figure 6 illustrated the interaction effects of injection pressure and load on volumetric efficiency for different nozzles. VE is defined as the volume flow rate of air into the intake system divided by the rate at which volume is displaced by the piston. Lower value of volumetric efficiency is preferable for the diesel engine. All four figures presented that for any specified value of injection pressure, VE decreases with increase in load. This may be because the combustion is improved due to higher in-cylinder temperature after successive working of engine at high load and this high temperature in cylinder decreases the volumetric efficiency. Graph for 3 hole nozzle showed that the lowest VE is 80.275 % at 240 bar for 10 kg load. Graph of 4 hole axis angle of 142°nozzle showed that VE increases with increase in injection pressure of (200-210) bar and then tends to decrease with further increase in injection pressure for 6 kg, 8 kg and 10 kg load. While 2 kg and 4 kg load shows a little different nature with increase in VE from 230 to 240 bar.The lowest VE was 78.4 % at 245 bar for 10 kg load. Graph of 4 hole 150°hole axis angle represented the different nature of graph for VE compared to 4 hole 142°hole axis angle. The lowest VE was 80.338 % at 200 bar for 10 kg load.The lowest VE achieved for 5 hole injector nozzle was 78.816 % at 250 bar for 10 kg load.

Air Fuel Ratio (AFR):

Figure 7 illustrated the interaction effects of injection pressure and load on AFR for 3 hole, 4 hole (142°and 150°) hole axis angle and 5 hole nozzles. Thermal engines use fuel and oxygen (from air) to produce energy through combustion. AFR is the ratio between mass of air to mass of fuel in the air-fuel mixture used by an engine when running. Diesel engines always run on lean air-fuel mixture. The figures for AFR represent that for any specified value of injection pressure, AFR decreases with the increase in load. Graph for 3 hole showed that AFR tends to increase with further increase in injection pressure in the range of (225-240) bar. Again, after 245 bar injection pressure, AFR tends to decrease. The lowest AFR was 22.766 at 250 bar for 10 kg load. Graphs for 4 hole nozzle of 142°hole axis angle depicted that AFR almost tends to decrease with increase in injection pressure for most of the variation of loads. The lowest AFR was 24.178 at 240 bar of 10 kg. Figure for 4 hole nozzle of 150°hole axis angle represented the lowest AFR as 15.417 at 250 bar for 10 kg load. It was clear from the graph of 5 hole nozzle that AFR increases with injection pressure of 220 bar to 245 bar and almost every load has lower AFR at 250 bar except 2 kg and 10 kg. The graphs depicted the lower AFR of 28.726 at 240 bar for 10 kg load.

Net Heat Release (NHR):

The interaction effects of injection pressure and loads on net heat release rate were shown in figure 8 for 3 hole, 4 hole (142°), 4 hole (150°) and 5 hole nozzle. It was clear from the graphs that NHR increases with the increase in load. Minimum NHR is obtained at lower load due to more heat transfer to cylinder surface.From the graph of 3 hole nozzle, it was clear that with increase in injection pressure, NHR increases for any specified value of load. The highest NHR obtained was 63.762 J/deg at 250 bar at 10 kg load. 4 hole nozzle of 142°hole axis angle showed that for higher loads NHR increases with increase in injection pressure but with further increase in injection pressure from 220 bar to 245 bar, NHR decreases. This may happen due to the delayed injection, which adverse the effect on the fuel air mixture formation. The highest NHR obtained was 47.909 J/deg at 250 bar at 10 kg load. 4 hole nozzle of 150°hole axis angle showed the similar nature of graph of 3 hole nozzle for 2 kg, 4 kg, 6kg and 8 kg load. Here, NHR increases from 220 bar to 250 bar due to increase in cylinder pressure and combustion temperature. This may be due to improved premixed combustion phase which could be due to better atomization and improved air fuel mixing. Higher value of NHR was 50.106 J/deg at 250 bar at 6 kg. The graphs of 5 hole nozzle showed different nature of NHR for different loads with increase in injection pressure.5 hole nozzle gives the higher NHR of 59.476 J/deg at 245 bar at 10 kg.

Maximum Cylinder Pressure (MCP):
Figure 9 showed the interaction effect of injection pressure and loads on MCP for 3 hole, 4 hole of 142°, 4 hole of 150°and 5 hole nozzles. It was clear from the graphs that for any specified value of injection pressure, MCP increases with increase in load. For 3 hole injector nozzle, MCP first decreases with the increase in injection pressure from 200 to 215 bar then again it increases with further increase in injection pressure. On a diesel engine, the occurrence of MCP mainly depends on amount of fuel burnt in the uncontrolled combustion phase and ignition delay period. 65.129 bar was maximum cylinder pressure for 3 hole nozzle at 240 bar at 10 kg. Similarly, for different nozzle holes and hole axis angle of 142°and 150°, MCP first slightly decreases with increase in injection pressure which may be due to longer delay period because of improper mixing of fuel leading to improper combustion, and again MCP increases with increase in injection pressure. Among two hole axis angle of 142°and 150°, maximum cylinder pressure of 65.33 bar was given by 4 hole 142º hole axis angle at 240 bar at 10 kg. The graph of 5 hole nozzle gave maximum cylinder pressure of 64.655 bar for 10 kg load at 210 bar injection pressure.

Mean Gas Temperature (MGT):
The figure 10 showed the interaction effect of injection pressure and loads on MGT for 3 hole, 4 hole of 142°, 4 hole of 150°and 5 hole nozzles. Mean gas temperature is the average gas temperature present inside the cylinder. It is clear from the graphs that for any specified value of injection pressure, MGT increases with the rise in load from 2 kg to 10 kg. Low temperature combustion brings benefits to engines in terms of both heat transfer (heat losses at the walls) and heat rejection to the exhaust. The graph of 3 hole nozzle and 4 hole nozzle of 142°hole axis angle showed that MGT slightly decreases in the range of (200-220) bar and then increases with the further increase in injection pressure. The lowest MGT given by 3 hole and 4 hole of 142°hole axis angle were 871.868 ºC and 857.683 ºC at 210 bar and 2 kg load respectively. 4 hole nozzle of 150°hole axis angle showed the different nature compared to 142°hole axis angle where MGT decreases in the range of 225 bar to 240 bar and the lowest MGT obtained was 836.86 ºC at 240 bar at 2 kg. For 5 hole nozzle, MGT decreases in the range of 215 bar to 250 bar for 2 kg, 4 kg, 8 kg and 10 kg load. For 6 kg load, MGT shows slightly different nature. The lowest MGT of 781.404ºC was given by 5 hole nozzle at 250 bar for 2 kg load.

6. Conclusions

The research work dealt with the experimental investigation on performance and combustion characteristics of a single-cylinder direct injection diesel engine when fueled with diesel for 3 hole, 4 hole of 142°hole axis angle, 4 hole of 150°hole axis angle and 5 hole nozzles using RSM based quadratic models constructed to explore the effects of the two process parameters: loads and injection pressure. Based on the experimental results and subsequent graphical analysis it was known that IP, BTE, NHR, MCP and MGT were increased and SFC, VE and AFR were decreased with the increase in load for any specified value of injection pressure for all different nozzles. 3 hole nozzle is best for given experimental engine because the value of vital engine parameters for performance like BTE and SFC and combustion like NHR were obtained better with 3 hole nozzle.

- IP increased with the increase in injection pressure after 230 bar onwards for 3 hole nozzle. The better value of IP was given by 220 bar for 4 hole nozzle of 150°hole axis angle. For 5 hole nozzle, IP went on decreasing with increase in injection pressure.

- It was revealed that for same load and injection pressure, among different 3, 4 and 5 hole nozzles, 3 hole nozzle had the higher BTE of 28.653% at 210 bar for 10 kg load. Also, among different hole axis angles of 4 hole nozzle, 142°hole axis angle had better BTE.

- Lowest SFC of 0.196 kg/kwh was obtained from 3 hole nozzle for 215 bar at 4 kg load. Increasing the number of nozzle holes from 3 to 5 resulted in the increased value of SFC.

- Lower value of VE is desirable for the diesel engine. Lowest VE of 78.41% was obtained from 4 hole nozzle of 142°hole axis angle at 245 bar for 10 kg load.

- For the similar injection pressure and load, increasing number of nozzle holes from 3 to 5 resulted in increased AFR. 4 hole nozzle of 150°hole axis angle had lowest AFR of 15.417 compared to other hole nozzles.

- NHR for 3 hole and 4 hole nozzle of 150 degree increased with the increase in injection pressure due to the increase in cylinder pressure and combustion temperature. 4 hole nozzle of 142°showed that NHR decreases with further increase in injection pressure. The better value of 63.762 J/deg was given by 3 hole nozzle at 250 bar at 10 kg load.

- For every different nozzle holes, with increase in injection pressure, MCP first slightly decreased and again MCP increases with increase in injection pressure. This may be due to proper atomization, better air fuel mixing and hence combustion. The maximum cylinder pressure of 65.33 bar was obtained for 10 kg load of 4 hole 142°hole axis angle at 240 bar injection pressure.

- MGT slightly decreased in the range of (200-220) bar and then increased with the further increase in injection pressure for 3 hole and 4 hole nozzle (142°) hole axis angle. 4 hole nozzle of 150°hole axis angle had different nature of MGT compared to 4 hole 142°. For 5 hole nozzle, MGT decreased in the range of 215 bar to 250 bar for most of the loads.

Acknowledgments

The authors acknowledge the guidance and support of the Thapathali Campus and Department of Automobile and Mechanical Engineering for the completion of this research.

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