Application of Taguchi Methods for the Optimization of Factors Affecting Engine Performance and Emission of Exhaust Gas Recirculation in Steam-injected Diesel Engines

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Abstract: In this study, optimal engine performance and pollutant emission conditions are investigated by using Taguchi Design Methods. Orthogonal arrays of Taguchi, the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) were employed to find the optimal levels and to analyze the effect of the operation conditions on performance and emission values. The parameters and their levels are engine speeds at 1200, 1600, 2000 and 2400 rpm, steam ratios of 0, 10, 20 and 30% and EGR ratios of 0, 10, 20 and 30%. Confirmation tests with the optimal levels of engine parameters were carried out in order to illustrate the effectiveness of the Taguchi optimization method. While steam and EGR ratios are found effective on emission parameters, significance levels for these parameters have been found low for effective power and torque. It was thus shown that the Taguchi method is suitable to solve the problems of performance and emissions for diesel engines.

Keywords: Taguchi Method; Diesel Engine; Pollutant Emissions; EGR; Steam

1 Introduction

With the growing awareness of environmental hazards, one of the most stringent problems that engineers and engine designers have encountered, in the process of diesel engine development, is the control and reduction of pollutant emissions to acceptable levels, as limited by relevant regulations. The emission rights applying to the relevant period are distributed amongst the actors of this market, keeping in mind that the permitted emission level should be gradually decreased from period to period by each actor [1]. Thus, ongoing developments in diesel emission control technologies are required to meet future emission regulations.

There are various methods for controlling NOx emissions in the open literature. Nowadays, the topics touching on water injection have become widely used methods to reduce NOx emissions [2-5]. Water can be supplied to the engine as a direct injection, water/fuel emulsification [6], hot water fumigation and steam injection. Alahmer et al. investigated the effect of emulsified diesel fuel and found that while improving NOx emissions, specific fuel consumption (SFC) increases [7]. Tauzi et al. analyzed the water injection into inlet manifold and observed that NOx emissions reduce significantly while increasing CO emissions with the raise of dilution ratio and SFC [8]. Ishida et al. investigated port water injection (fumigation) into diesel engine and observed that NOx emissions reduce about 50% [9]. Parlak et al. studied water injection in the form of steam phase into intake manifold and revealed that NOx emissions and SFC reduce effective power and torque increase with electronically controlled steam injection system [10].

EGR is another method for NOx reduction [11-15]. Haşimoğlu et al. examined the effects of EGR on diesel engine and found that although NOx emissions reduced considerably, smoke emissions and SFC deteriorated [16]. Mani et al. investigated the effect of cooled EGR using 100% waste plastic oil on diesel engine and observed that NOx, CO, CO_2 and smoke emissions decrease with the increase of EGR rate [17].

Although the NOx reduction rate with steam injection is reached up to 33% at full load condition, NOx can be decreased further by using EGR+steam injection combination. Kökkülünk [18] studied the effects of steam injected diesel engine with EGR on performance and emission parameters. However, there is a need to optimize the parameters considering engine performance and pollutant emissions. In this study, Taguchi methods are used in optimization of the factors affecting engine performance and emissions of EGR application on steam-injected diesel engine. In the experimental design; torque, effective power, SFC and emissions (NOx, CO, CO_2 and HC) are chosen as parameters and engine speed, EGR and steam ratio as factors. The conditions which maximize the torque and effective power and minimize the SFC and emissions were investigated.

2 Materials and Methods

2.1 Experimental Details

The experiments were carried out with a single cylinder, naturally aspirated, four-stroke Diesel engine. The engine specifications and experimental set-up are shown in Table 1 and Figure 1, respectively [19, 20].

Table 1
Engine specifications

Engine Type	Super Star
Bore [mm]	108
Stroke [mm]	100
Cylinder Number	1
Stroke Volume [dm^3]	0.92
Power, 1500 rpm, [kW]	13
Injection pressure [bar]	175
Injection timing [Crank Angle]	35
Compression ratio	17:1
Maximum speed [rpm]	2500
Cooling	Water
Injection	Direct Injection

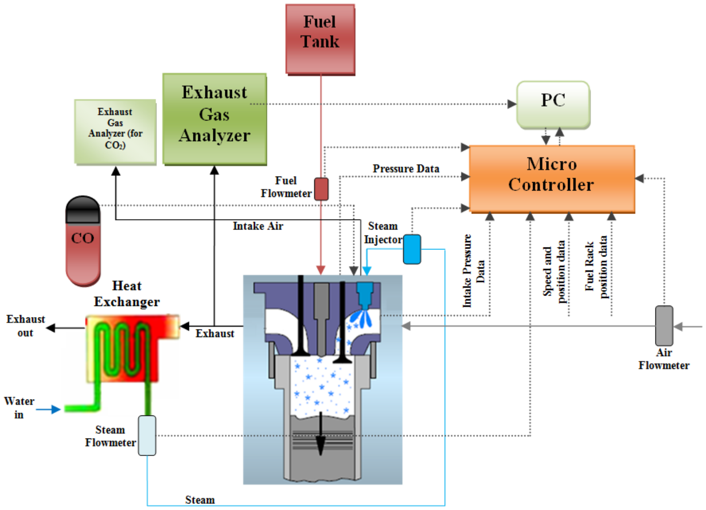

Figure 1
Experimental set-up

In order to measure brake torque, the engine is coupled with a hydraulic type dynamometer of 50 kW absorbing capacity using an “S” type load cell with the precision of 0.1 N. MRU Spectra 1600 L type and Bilsa Mod gas analyzers were used so as to measure exhaust gases [19, 20].

99% purity Linde Gas brand CO_2 gas was used for EGR application so as to the most compound in exhaust gases and to calibrate EGR ratio. Method of Needham et al. [21] was used in order to determine the amount of CO_2 gas. EGR percentage is:

$$\mathrm{EGR}(\%) = \frac{\mathrm{CO}_{2(\mathrm{intake\_manifold})} - \mathrm{CO}_{2(\mathrm{surroundings})}}{\mathrm{CO}_{2(\mathrm{exhaust\_manifold})}} \mathrm{x}100 \qquad (1)$$

Where $CO_{2(surroundings)}$ is the reference CO_2 percentage in surroundings. In this study, this value was neglected owing to being 0.03% in the literature [22]. EGR ratios were determined with a volume ratio of CO_2 value.

Experiments were done at the variable speeds 1200, 1600, 2000, and 2400 rpm at full load conditions. In the experiments, 0, 10, 20 and 30% steam and EGR ratios were carried out. The experiments were repeated for each steam and EGR ratio while performance and emission values were compared with those of a standard diesel.

2.2 Taguchi Design Method

In the literature, various studies have been conducted for optimizing parameters with Taguchi Design Method. Among them, Saravanan et al. investigated the effects of EGR rate, fuel injection timing and pressure in controlling NOx emission of diesel engine and experiments were designed as per Taguchi's L9 orthogonal array [23]. Ganapathy et al. analyzed thermodynamic model of Jatropha biodiesel fuelled engine by means of Taguchi method to assess the optimum engine design and operating parameters [24]. Parlak et al. studied the factors affecting emissions of a diesel engine fuelled tobacco oil seed methyl ester with Taguchi approach [25]. Win et al. investigated the effects of static injection timing, nozzle/valve opening pressure, nozzle tip protrusion, number of holes, plunger diameter, load torque, nozzle hole diameter, and engine speed on engine noise, combustion noise, smoke level, fuel economy, and exhaust emissions of a diesel engine [26]. Sivaramakrishnan et al. used Taguchi methods to optimize the diesel engine in regard to brake power, fuel economy and emissions [27].

The above studies, conducted by researchers, show that Taguchi methods provides effective solutions for investigating the effect of parameters on the performance and emissions of diesel engine. In the present study, experiments were designed to apply the Taguchi's methods to establish the effects of four (4) engine speed, steam and EGR ratios for the purpose of determining optimal conditions of performance and exhaust emissions. Three design factors and their levels are given in Table 2.

Table 2

Design factors and levels

Symbols	Factors	Level 1	Level 2	Level 3	Level 4
A	Engine Speed (rpm)	1200	1600	2000	2400
B	Steam Ratio (%)	0	10	20	30
C	EGR Ratio (%)	0	10	20	30

In Taguchi methods, the signal-noise (S/N) ratio is used to represent a performance characteristic and there are three types of S/N ratios; the lower-the better, the higher-the better and the more nominal-the better [27]. In this study, the lower-the better was used for SFC, NOx, CO, CO_2 and HC emissions and the higher-the better for torque and effective power. These three different S/N ratios are expressed in Table 3, where n and Y is the number of repeated experiment and the measured value of the response variable, respectively.

Table 3

S/N Ratios Formulations

The lower-The better	$S/N = -10\log(\sum Y^2/n)$
The higher-The better	$S/N = -10\log(\sum(1/Y^2)/n)$
The more nominal-The better	$S/N = 10\log(\sum \bar{Y}^2/S^2)$

The orthogonal array mixed L_{16} selected as shown in Table 4, which has 16 rows corresponding to the number of tests with all columns at four levels and the factors and the interactions are assigned to the columns [28].

Table 4

Experimental Plan of L_{16}

Experiments No.	Designation	Factors		
		(A)	(B)	(C)
1	$A_1B_1C_1$	1	1	1
2	$A_1B_2C_2$	1	2	2
3	$A_1B_3C_3$	1	3	3
4	$A_1B_4C_4$	1	4	4
5	$A_2B_1C_2$	2	1	2
6	$A_2B_2C_1$	2	2	1
7	$A_2B_3C_4$	2	3	4
8	$A_2B_4C_3$	2	4	3
9	$A_3B_1C_3$	3	1	3
10	$A_3B_2C_4$	3	2	4
11	$A_3B_3C_1$	3	3	1
12	$A_3B_4C_2$	3	4	2
13	$A_4B_1C_4$	4	1	4
14	$A_4B_2C_3$	4	2	3
15	$A_4B_3C_2$	4	3	2
16	$A_4B_4C_1$	4	4	1

3 Results and Discussion

The measurement of the effective performance of motor vehicles takes place by means of bench tests [29]. In this study, the optimum values of the factors (engine speed, steam and EGR ratios) affecting engine performance and emissions of EGR application on steam injected diesel engine were determined by using Taguchi methods.

Table 5 shows the analysis of variance of experimental data. Effective power, torque, SFC, CO, $CO_{2,}$ NOx and HC are determined between 96.5% and 99% confidence levels.

Table 5
ANOVA results

Factors		Sum of squares (SS)	Degree of Freedom (v)	Variance, VT	F_{factor}
Torque*	[A] Engine	174.49	3	58.16	60.49
	[B] Steam ratio	0.83	3	0.28	0.29
	[C] EGR ratio	9.29	3	3.10	3.22
	Error	5.77	6	0.96	
	Total	190.39	15	12.69	
Effective Power***	[A] Engine	72.49	3	24.16	546.53
	[B] Steam ratio	0.08	3	0.03	0.59
	[C] EGR ratio	0.39	3	0.13	2.92
	Error	0.27	6	0.05	
	Total	73.23	15	4.88	
SFC***	[A] Engine	6390.38	3	2130.13	288.96
	[B] Steam ratio	258.37	3	86.12	11.68
	[C] EGR ratio	1156.86	3	385.62	52.31
	Error	44.23	6	7.37	
	Total	7849.85	15	523.32	
NOx**	[A] Engine	41148	3	13716	14.97
	[B] Steam ratio	8346	3	2782	3.04
	[C] EGR ratio	384774	3	128258	139.95
	Error	5499	6	916.5	
	Total	439767	15	29317.8	
CO***	[A] Engine	3.08	3	1.03	123.35
	[B] Steam ratio	0.09	3	0.03	3.94
	[C] EGR ratio	2.15	3	0.72	86.02
	Error	0.05	6	0.01	
	Total	5.38	15	0.36	
CO_2***	[A] Engine	23.76	3	7.92	40.87
	[B] Steam ratio	7.12	3	2.37	12.25
	[C] EGR ratio	88.37	3	29.46	151.99
	Error	1.16	6	0.19	
	Total	120.41	15	8.03	
HC*	[A] Engine	2639.99	3	880	24.07
	[B] Steam ratio	367.70	3	122.57	3.35
	[C] EGR ratio	3385.70	3	1128.57	30.87
	Error	219.39	6	36.57	
	Total	6612.77	15	440.85	

**** At least 99% confidence*
*** At least 98.5% confidence*
** At least 96.5% confidence*

3.1 Exhaust Emissions

S/N values of factor levels of HC, NOx, CO and CO_2 emissions for engine speed, steam and EGR ratios are shown in Figure 2. As a result of study, by using the Taguchi approach, it is shown that engine speed and EGR ratios have been found to be significant in exhaust emissions. However, steam ratio has affected the exhaust emission in a different level.

After confirmation tests were carried out, the optimum design conditions were found as $A_4B_4C_1$ (2400 rpm, 30% steam ratio, 0% EGR) for CO and $A_1B_4C_1$ (1200 rpm, 30% steam ratio, 0% EGR) for CO_2. As can be seen from the Figure 2a, the effect of steam on CO_2 emissions have been found meaningful for only 10% steam ratio in 99% confidence level. On the other hand, CO has been found significant up to 20% steam ratios tested (Figure 2b).

As can be seen from Figure 2c and Figure 2d, after confirmations test carried out in 96.5% confidence level, the optimum design parameter combination were found as $A_4B_3C_1$ (2400 rpm, 20% steam, 0% EGR) for HC emissions and $A_4B_2C_4$ (2400 rpm, 10% steam, 30% EGR) for NOx with the 98.5% confidence level. However, there is not a meaningful change except for the 10% steam ratio for the NOx emissions.

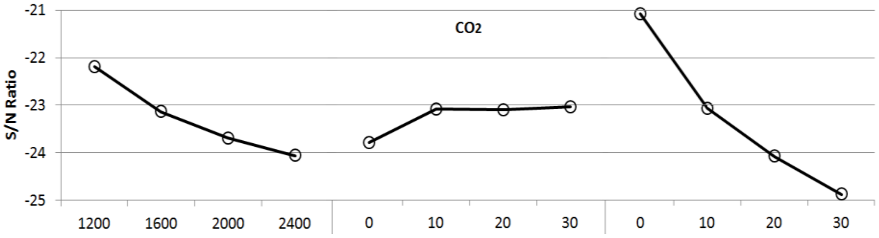

Figure 2 (a)

S/N values of factor levels for CO_2

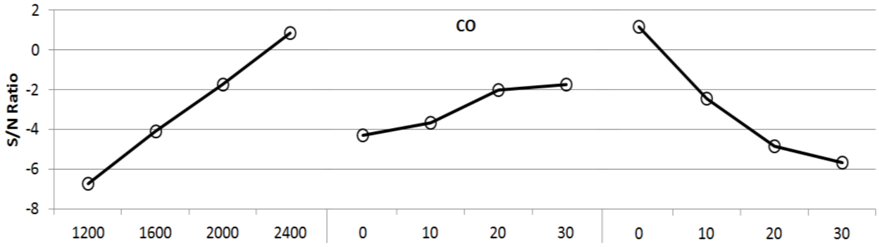

Figure 2 (b)

S/N values of factor levels for CO

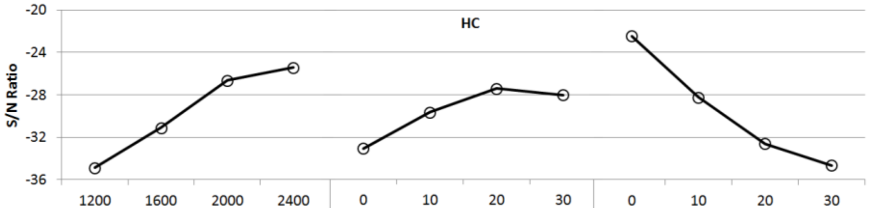

Figure 2 (c)

S/N values of factor levels for HC

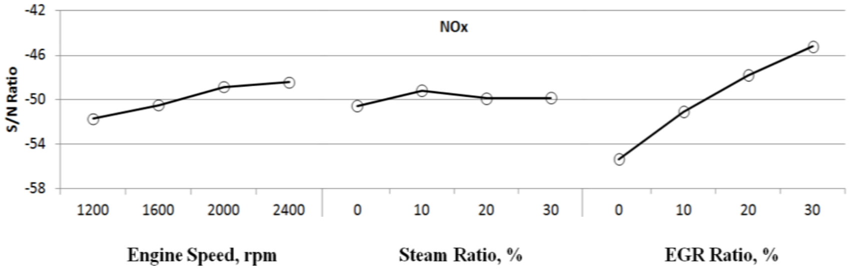

Figure 2 (d)
S/N values of factor levels for NOx

In conclusion, EGR has a distinct effect on NOx, in comparison to steam injection. But, when considering the negative effects of EGR on performance parameters, EGR could not be evaluated individually, as a method for reducing NOx emissions. Furthermore, when evaluating all exhaust emissions, steam injection become more significant, up to 20%.

3.2 Performance Parameters

S/N values of factor levels of SFC, effective power and torque for engine speed, steam and EGR ratios are shown in Figure 3. As a result of study by using the Taguchi approach, it is shown that engine speed has been found to be significant on performance parameters. However, steam and EGR ratios have affected exhaust emissions in a different level.

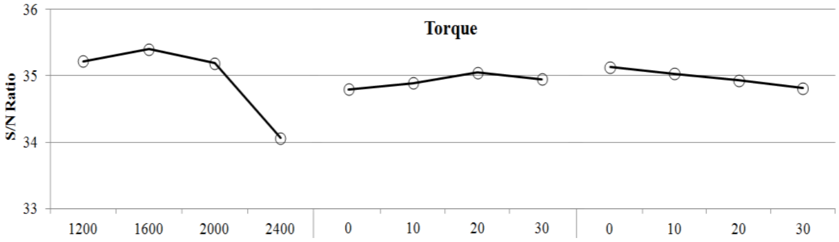

Figure 3 (a)
S/N values of factor levels for Torque

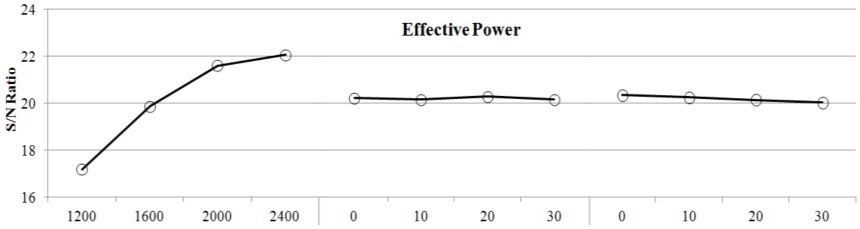

Figure 3 (b)
S/N values of factor levels for Effective Power

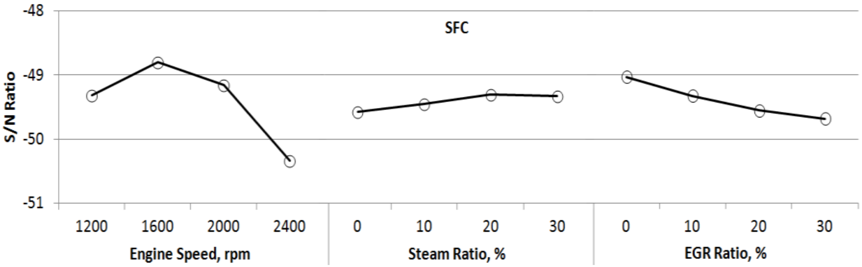

Figure 3 (c)
S/N values of factor levels for SFC

After confirmation tests carried out at a 99% confidence level, the optimum design parameter combination were found as $A_2B_3C_1$ (1600 rpm, 20% steam, 0% EGR) for SFC, $A_4B_3C_1$ (2400 rpm, 20% steam, 0% EGR) for effective power and with 96.5% confidence level, $A_2B_3C_1$ (1600 rpm, 20% steam, 0% EGR) for torque.

As can be seen from Figure 2d, $A_4B_2C_4$ is the optimum design parameter for NOx emissions. However, the optimum steam ratio is 10% for NOx, 20% for SFC. In addition, with regards to SFC, the minimum fuel consumption is found with a 0% EGR ratio.

Moreover, the effect of steam and EGR ratios, for effective power, become meaningful comparing with standard diesel and in the case of steam injection, there is not significant change between 10%-30%.

When considering both effective power and torque values, there is not a significant change in effective power and torque with the increase in EGR ratios. The reason of the limited reduces in effective power with the increase of EGR ratios could be derived from steam injection.

Table 6 and Table 7 show the comparison with experimental data and S/N ratios of calculated values for exhaust emissions.

Table 6
Experimental values and S/N ratios for exhaust emissions

Exp. No.	NOx		CO		CO_2		HC	
	Exp. val.	S/N	Exp. val.	S/N	Exp. val.	S/N	Exp. val.	S/N
1	697.30	-56.87	1.82	-5.23	10.35	-20.29	37.60	-31.50
2	448.00	-53.03	2.03	-6.15	12.20	-21.72	52.41	-34.38
3	316.14	-49.99	2.29	-7.19	14.20	-23.04	62.86	-35.96
4	220.15	-46.85	2.62	-8.38	15.30	-23.69	76.40	-37.66
5	426.20	-52.59	1.60	-4.08	15.16	-23.61	41.50	-32.36
6	588.35	-55.39	1.16	-1.29	11.06	-20.87	16.76	-24.48
7	191.12	-45.63	1.99	-6.01	16.55	-24.37	53.05	-34.49
8	261.61	-48.35	1.80	-5.11	15.28	-23.68	45.09	-33.08
9	228.60	-47.18	1.76	-4.91	17.55	-24.88	50.80	-34.11

10	135.35	-42.63	1.82	-5.20	17.97	-25.09	40.87	-32.22
11	587.62	-55.38	0.64	3.88	11.73	-21.38	6.68	-16.49
12	324.15	-50.21	1.10	-0.83	14.77	-23.38	15.42	-23.76
13	192.18	-45.67	1.42	-3.08	20.82	-26.36	51.40	-34.21
14	191.93	-45.66	1.28	-2.14	17.16	-24.69	23.43	-27.39
15	265.23	-48.47	0.87	1.21	14.95	-23.49	13.53	-22.62
16	494.58	-53.88	0.43	7.33	12.16	-21.69	7.530	-17.53

Table 7
Experimental values and S/N ratios for performance parameters

Exp. No	Torque		Effective Power		SFC	
	Exp. val.	S/N	Exp. val.	S/N	Exp. val.	S/N
1	57.64	35.21	7.24	17.19	284.64	-49.08
2	58.72	35.37	7.37	17.35	289.37	-49.22
3	57.29	35.16	7.19	17.14	296.07	-49.42
4	56.93	35.10	7.15	17.08	298.47	-49.49
5	59.79	35.53	10.01	20.01	277.56	-48.86
6	59.43	35.48	9.95	19.96	268.07	-48.56
7	58.00	35.26	9.71	19.74	279.62	-48.93
8	58.36	35.32	9.77	19.80	277.09	-48.85
9	58.01	35.26	12.14	21.68	298.00	-49.48
10	55.50	34.88	11.61	21.30	298.18	-49.48
11	58.72	35.37	12.29	21.79	270.08	-48.62
12	57.64	35.21	12.06	21.63	282.97	-49.03
13	49.77	33.93	12.50	21.93	347.62	-50.82
14	49.77	33.93	12.50	21.93	334.13	-50.47
15	49.77	33.93	12.50	21.93	322.63	-50.17
16	52.63	34.42	13.22	22.42	311.70	-49.87

In Taguchi methods, verification experiments should be done to determine optimum conditions and compared with experimental values. In this study, all values are within confidence levels, as a result of the verification experiments.

Conclusion

In this study, the effects of the factors (engine speed, steam and EGR ratios) on engine performance and emissions of an EGR application, with a steam injected diesel engine have been investigated using the Taguchi approach. Verification experiments were performed to compare with the Taguchi results and have a good agreement with the experimental data.

It is observed from the results, that effective power, SFC, CO and CO_2 are determined at least 99%, NOx at least 98.5% and torque, HC at least 96.5% confidence levels.

The optimum design parameter combinations have been found as $A_4B_4C_1$ (2400 rpm, 30% steam, 0% EGR), $A_1B_4C_1$ (1200 rpm, 30% steam, 0% EGR) for CO and CO_2, respectively and $A_4B_3C_1$ (2400 rpm, 20% steam, 0% EGR) and $A_4B_2C_4$ (2400 rpm, 10% steam, 30% EGR) for HC and NOx emissions, respectively.

For the performance parameters, the optimum design parameter combinations have been found as $A_2B_3C_1$ (1600 rpm, 20% steam, 0% EGR) for SFC, $A_4B_3C_1$ (2400 rpm, 20% steam, 0% EGR) for effective power and $A_2B_3C_1$ (1600 rpm, 20% steam, 0% EGR) for torque.

The optimum steam ratio is 10% for NOx and 20% for SFC. On the contrary, with regards to SFC, the minimum fuel consumption has been found with a 0% EGR ratio. For effective power and torque values, there is not considerable change in effective power and torque with an increase in EGR ratios. The reason of a limited reduction in effective power with the increase of EGR ratios could be explained due to steam injection.

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