Optimizing injection pressure of four stroke four cylinder diesel engine for low emissions using Taguchi method

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***Abstract* - This study involves theoretical aspects of four Stroke four Cylinder Diesel Engine system. This study investigates the experimental performance of four Stroke four Cylinder Diesel Engine system. For this aim, an experimental system consisting of original components from four Stroke four Cylinder Diesel Engine systems, system has been set up and instrumented. The system is suggested to test under steady-state operating conditions. Four stroke Four cylinder diesel engine model has been analyzed experimentally. To optimize injection pressure of diesel engine from 100 bar to 250 bar with the increment of 50 bar by shim adjusting inside the atomizer for increasing engine performance values such as power, torque, and specific fuel consumption have been measured and minimize emission of engine using Taguchi method. According to results, by optimizing injection pressure, the maximum performance has been obtained at 150 bar. In addition, high injection pressure for O_2 and CO_2, low injection pressure for NO_x and smoke level must be preferred for decreasing emissions.**

***Key Words* - Diesel Engine, Effect of Injection Pressure on Engine Performance and Emissions**

I. INTRODUCTION

Injection Pressure

In diesel engine, when fuel injection pressure is low the fuel particle diameters will enlarge and ignition delay period during the combustion will increase. This situation leads to increase pressure. SO, NOx and CO emissions will increase since combustion process goes to a bad condition. When injection pressure is increased fuel particle diameters will become small. Since formation of mixing of fuel to air becomes better during ignition period, smoke level and CO emission will be less. But, if injection pressure is too higher ignition delay period becomes shorter. So, possibilities of homogeneous mixing decrease and combustion efficiency falls down. Therefore smoke is formed at exhaust of engine.

Injection Pressure Depends On
- Injection nozzle
- Spring assembly

Functions of Injection Nozzles Atomizes the fuel for better combustion spreads the fuel spray to fully mix with air.

Nozzle Injection Pressure Adjustment

- Screw adjustment
- Shim adjustment

Shim Adjustment

- Injection pressure was altered by adjusting the number of shims under the atomizer. When the number of shims were added pressure was retarded. Changing the nozzle spring tension changed the nozzle opening pressure. Nozzle pressure was measured using pressure gauge.
- When the spring preload was increased by putting the shim below the pressure spring the nozzle opening pressure was increased.
- Injection pressure was changed between 100 bar to 250 bar with the increment of 50 bar. Varying the adjusting shim thickness by 0.025mm (0.0010 in) changes the injection pressure by about 373kpa (3.8 kgf/cm^2).

Optimization of injection pressure was done by Taguchi method. Orthogonal arrays are significant parts of Taguchi method. Instead of one factor at a time, all factors are varied simultaneously as per the design array and the response values are observed. It has the ability to evaluate several factors in a minimum number of tests. Design of experiments (DOE) approach is cost effective and the parameters are varied simultaneously and then through statistical responsible for the engine emissions and fuel analysis the contribution of individual parameters towards the response value observed also could be found out. The operating parameters are injection pressure, engine speed and responsible parameters are power, torque, SFC, O_2, CO_2, CO and NO_x. In this work DOE approach is used to find the effect of operating parameters on power, torque, SFC, O_2, CO_2, CO and NO_x emissions.

II. LITERATURE REVIEW

Literature study is required to understand the correct objective of the project work. The past research work gives the better idea and clear contain of cognition. It helps us to reach to a particular destination. The goal is "Optimizing injection pressure of four stroke four cylinder diesel engine for low emissions using Taguchi method".

Ismet Celıkten, [1] presented an experimental investigation of the effect of the injection pressure on engine performance and exhaust emission in indirect injection diesel engines. In this experimental study, effects of injection pressure on engine performance and exhaust emissions have been investigated. Experiments have been performed on a turbocharger diesel engine with 1-cylinder, 4-stroke, indirect injection. Emissions and engine performance values such as break main effective pressure, specific fuel consumption, and fuel flow have been measured both full and part loads by changing injection pressure from 150 to 250 bar and for different throttle positions. According to results, maximum performance has been obtained at 200 bar. In addition, high injection pressure for SO_2, and CO_2, low injection pressure for NO_x, and smoke level must be preferred for decreasing emissions.

Can Cinara, et al, [2] presented the effects of injection pressure and intake CO_2 concentration on performance and emission parameters of an IDI turbocharged diesel engine. The investigation was conducted on a four stroke, four-cylinder, indirect injection (IDI), turbocharged diesel engine and was concerned with the effect of using diluting CO_2 in the intake manifold and injection pressure on engine torque, power, brake mean effective pressure, specific fuel consumption, carbon monoxide, smoke and NO_x emissions. The tests have demonstrated that NO_x is reduced by the introduction of CO_2 in the inlet charge.

A.P. Carlucci, et al, [3] presented the analysis of the relation between injection parameter variation and block vibration of an internal combustion diesel engine. The development of combustion in diesel engines is strictly dependent on injection parameters, like injection number and timings, fuel quantity and mean injection pressure. Moreover, it is well known that the variation of the injection parameters has an effect on the engine block vibration. Hence, the present work aims at investigating the possibility of using engine block vibration as a mean to diagnose, outwardly, the combustion modifications induced by these parameters. So, the possibility of following the combustion modifications by means of two accelerometers positioned at two different zones of the engine block has been analysed, defining a characteristic ''signature'' for each parameter. Classical Fourier analysis and time–frequency analysis were used to define the degree of correlation between in-cylinder pressure and vibration signals. It has been proved that injection pressure and injected quantities, over an energy release threshold, really affect the vibration signals in a peculiar way; injection timing affects the engine block vibration in a less evident way, but a characteristic signature was also defined for this factor.

Gorkem Kokkulunk, et al, [4] presented the Theoretical and experimental investigation of diesel engine with steam injection system on performance and emission parameters. In the present study, a new electronically controlled steam injection method is applied to a direct injection (DI) diesel engine to control NO_x emissions. This method can be also used to improve the performance and efficiency. Steam injected diesel engine is modelled by using zero-dimensional single-zone combustion model for 20% steam ratio at full load condition. The obtained results are compared with conventional diesel engine in terms of performance and NO, CO, CO_2, HC emissions. The simulation results agree with experimental data quite well. In the experimental results, it is determined that the engine torque and the effective power increase up to 2.5% at 1200 rpm, specific fuel consumption (SFC) and effective efficiency improves up to 6.1% at 2400 rpm, NO emissions reduce up to 22.4% at 1200 rpm, CO_2 emissions decrease up to 4.3% at 1800 rpm, smoke density increases from 44% to 46% at 2200 rpm. This paper may be a leading essential tool for the real-engine designers by considering the effects of steam injection into the engine cylinder.

After reading all above research paper, concluded that reduce the emission of engine by optimization of injection pressure, proper heat balancing of engine required for maximum output, minimum fuel consumption, highest mechanical efficiency, highest break thermal efficiency, highest indicated thermal efficiency and with least emission of exhaust gas.

III. EXPERIMENTAL SETUP AND ANALYSIS

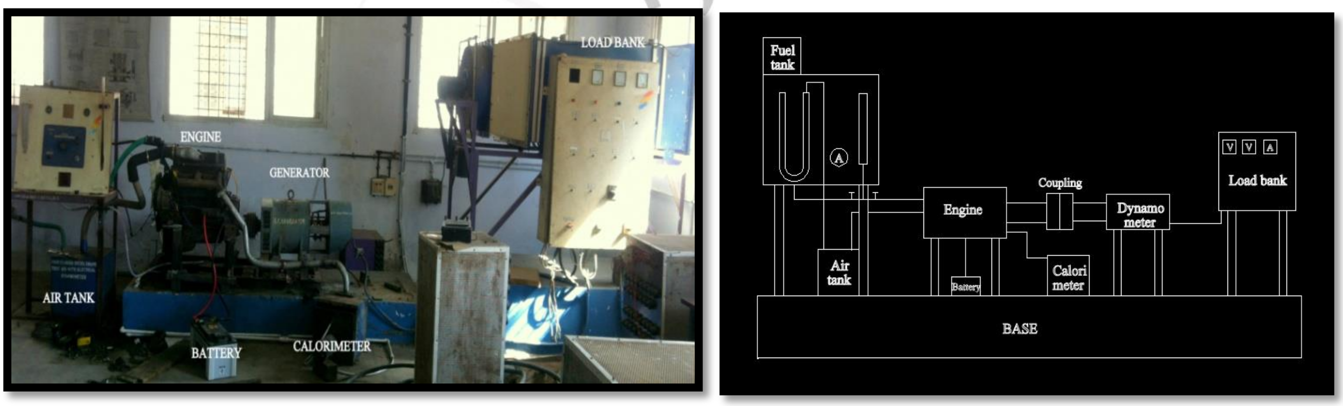


Figure 1: Experimental Set-Up

The present study was conducted on a TATA-407, diesel engine. The engine is four stroke four cylinder direct injection engine with a swept volume of 2956 cc. A Kirloskar brand electrical dynamometer was used for engine loading. The setup has stand-alone type independent panel box consisting of air tank, fuel tank, manometer, fuel measuring unit. Engine jacket cooling water inlet, outlet and calorimeter temperature is displayed on temperature indicator. Flow meters are provided for cooling water and calorimeter flow measurement. In addition, exhaust emission measurement equipment worked separately. The equipment was used for O_2, CO, CO_2 and NO_X measurements. After nozzles that injection pressure was changed between 100 bar to 250 bar with the increment of 50 bar. Injection pressure was changed by means of adjusting shim inside the injector so change injection spring tension. They are investigated according to the engine performance and emission for optimum injection pressure.

Characteristics Of Instrumentation		
Measured variable	**Instrument**	**Range**
Voltage	Voltmeter	0 to 500V AC
Current	Ammeter	0 to 120A
Engine speed	Tachometer	10 to 9999 rpm
Pressure	Pressure Gauge	0 to 400 bar
O_2, NO_x, CO, CO_2	Exhaust Multi-Gas analyzer	---

3.1 Procedure of Adjusting Shim

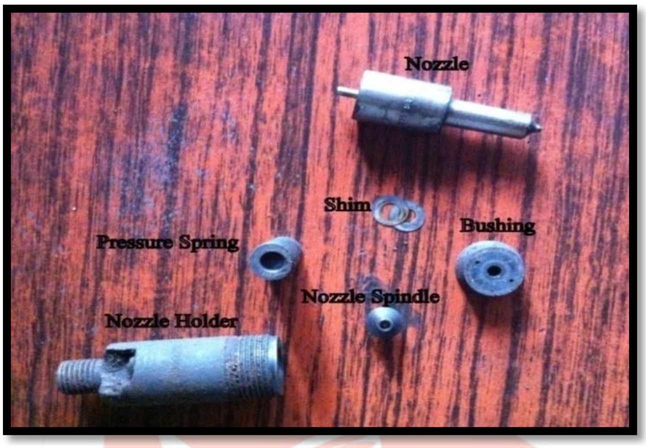
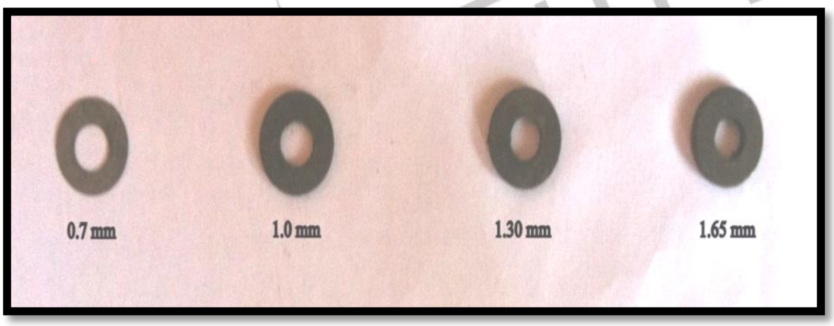


Figure 2: Different Parts of Injector

- Before starting engine, the nozzles were taken off and adjust injection pressure.
- For the adjustment, shim (washer) has been used to change the nozzles pressures.
- Read the release pressure in PSI.
- Hold pressure with handle just before release point and check for injector leaks.
- Disassemble the injector to inspect and clean.
- Select thicker or thinner shim washer to change pressure.
- Measure shims with dial caliper to confirm correct size.
- Clean, oil, and reassemble injector to proper torque.
- Repeat test and re-adjust pressure if needed.



Size of shim (mm)	Pressure (bar)
0.7	100
1.0	150
1.30	200
1.65	250

Figure 3: Different Size of Shim

3.2 Observation Table of Varying Injection Pressure

Pressure (bar)	Engine Speed (rpm)	Power (KW)	Torque (N.m)	SFC (g/kwh)	O_2 (%)	CO_2 (%)	CO (ppm)	NO_x (ppm)
100	1500	15.80	96.42	303.85	2.31	13.91	3795.92	285.98
	2000	24.81	117.38	281.31	2.84	13.55	755.10	351.27
	2500	32.40	123.65	277.06	3.95	13.13	734.69	408.60
	3000	37.96	121.65	274.90	4.38	12.86	204.08	456.37

150	1500	16.86	104.39	354.57	1.94	12.30	3918.36	332.17
	2000	27.78	131.09	293.85	2.74	12.45	1020.41	407.00
	2500	35.65	134.61	281.77	3.13	12.52	285.71	453.18
	3000	41.49	130.66	283.27	4.07	12.15	102.8	510.51
200	1500	13.02	84.95	305.42	4.88	11.90	3775.51	333.76
	2000	20.06	94.95	293.85	5.14	11.60	2061.22	375.16
	2500	29.63	114.17	277.58	8.88	10.99	102.04	494.59
	3000	35.30	112.71	277.51	6.37	11.77	20.41	596.50
250	1500	11.35	72.24	290.26	6.87	10.73	2759.22	354.46
	2000	16.63	79.00	278.69	6.81	10.50	512.04	427.70
	2500	25.35	94.74	275.49	7.07	10.31	89.67	531.21
	3000	32.67	103.98	273.85	7.47	9.98	11.45	424.52

3.3 Taguchi Method

- Taguchi technique is used to identify the key factors that make the greatest contributions to the variation in response parameters of interest.
- Taguchi recommends orthogonal array (OA) for laying out of the experiments which is significant part of this method. Instead of varying one factor at a time, all factors are varied simultaneously as per the design array and the response values are observed.
- It has the ability to evaluate several factors in a minimum number of tests. The results of the experiments are analyzed to achieve the following objectives.
  - To establish the optimum conditions for the NO_x, CO emissions and engine performance.
  - To estimate the contributions of individual parameter to the response.
  - To predict the response under optimum conditions.
- The optimum condition is identified by studying the main effects of each of the parameters. The main effects indicate the general trend of influence of each parameter.

3.3.1 Steps of Taguchi Method

- Identifying the response functions and control parameters to be evaluated.
- Determining the number of levels of the control parameters.
- Selecting the appropriate orthogonal array, assigning the parameters to the array and conducting the experiments.
- Analyzing the experimental results and selecting the optimum level of control parameters.

3.4 Experimentation and Analysis

- **Selection of Control Parameters**
  The control parameters are injection pressure and engine speeds were selected for the investigation, since they have influence on the objectives of reduction of emissions and improving the engine performance. Four levels were chosen for this investigation.
- **Selection of Orthogonal Array**
  Orthogonal array of L16 was selected based on the number of parameters and the levels. Minimum number of experiments= (L-1) P +1 where L is the number of levels and P is the number of parameters.
- **Setting Optimum Conditions and Prediction of Response Variables**
  The next step in Taguchi analysis is determining optimal conditions of the control parameters to give the optimum responses. In this work the response variables to be optimized were NO_x, CO_2, CO emissions and SFC are to be reduced as much as possible. Hence, the optimum parameter settings will be those that give minimum values of the NO_x, CO_2, CO emissions and SFC. The optimum settings of the parameters were achieved from the S/N ratio of the control parameters and those parameters that give the smaller S/N ratio values were selected.
  SN Ratio is determined according to the following equation:
  Where SN Ratio "smaller is better"

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\sum_{i=1}^{i=n} y_i^2\right]$$

Where SN Ratio "larger is better"

$$\frac{S}{N} = -10\log\left[\frac{1}{n}\sum_{i=1}^{i=n} \frac{1}{y_i^2}\right]$$

Where, $\frac{S}{N}$ = Signal to noise Ratio,

n = No. of measurements,

y_i = measured value at level i

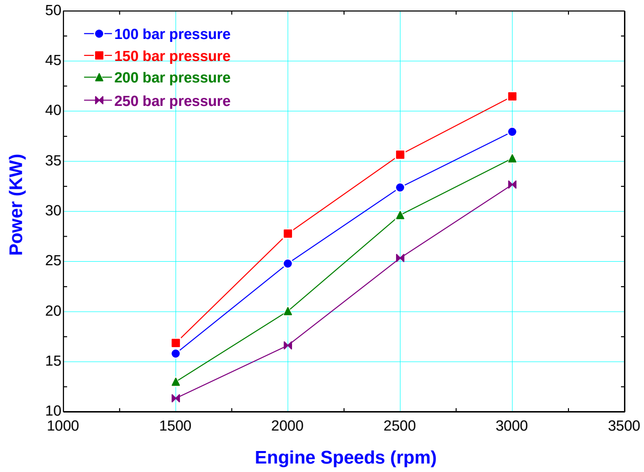


Figure 4: Power Vs Engine Speeds

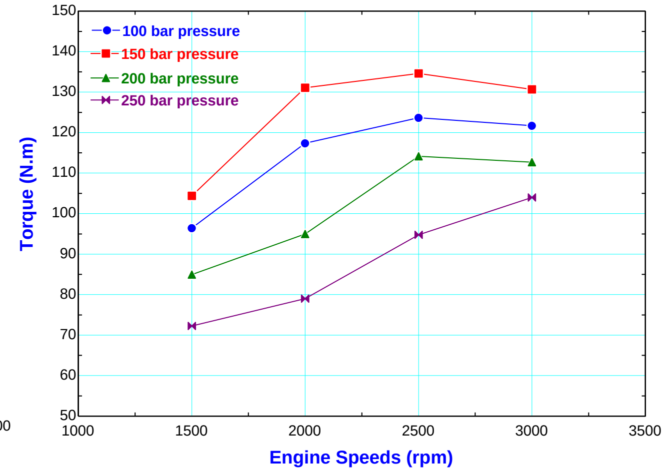


Figure 5: Torque Vs Engine Speeds

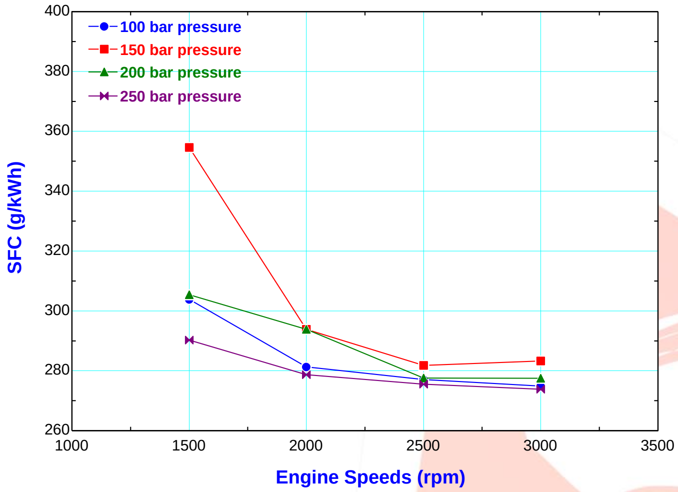


Figure 6: Specific Fuel Consumption Vs Engine Speeds

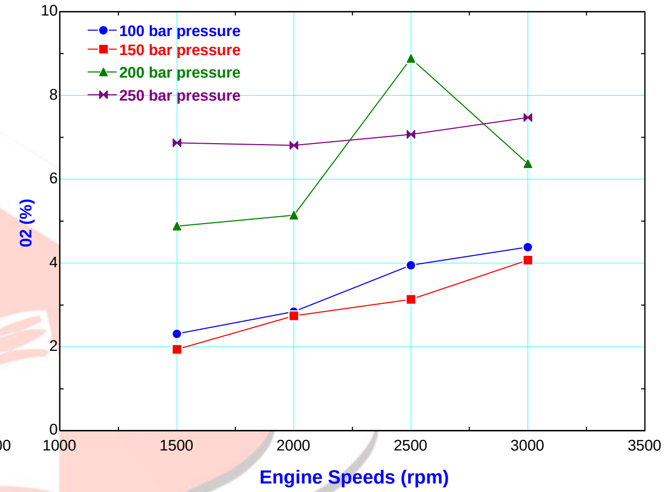


Figure 7: O_2 Vs Engine Speeds

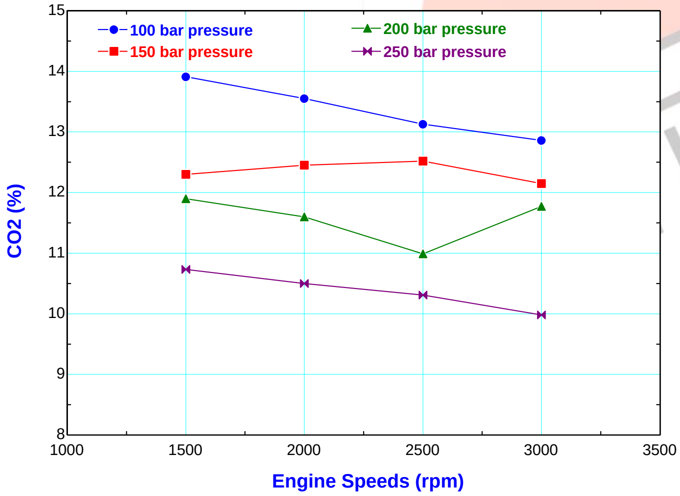


Figure 8: CO_2 Vs Engine Speeds

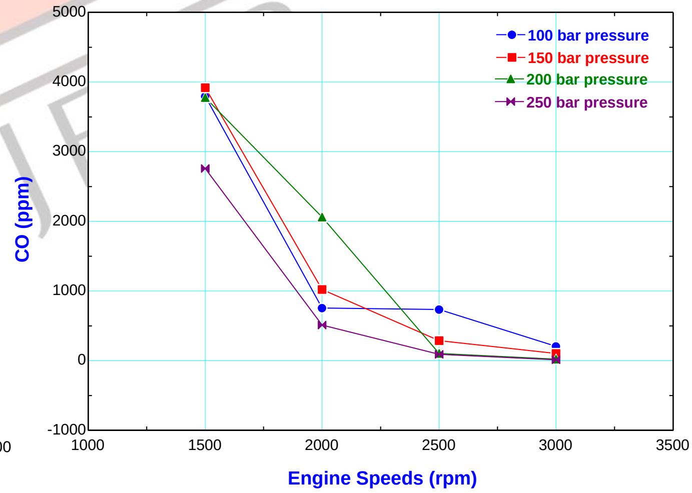


Figure 9: CO Vs Engine Speeds

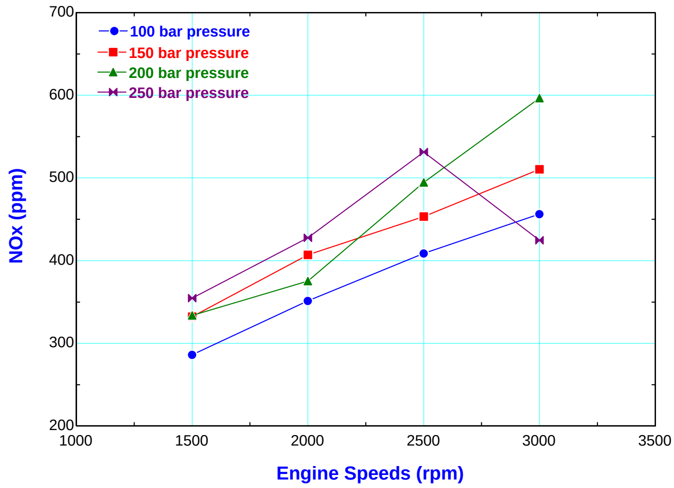


Figure 10: NO_X Vs Engine Speeds

Optimization Result Using Taguchi Method

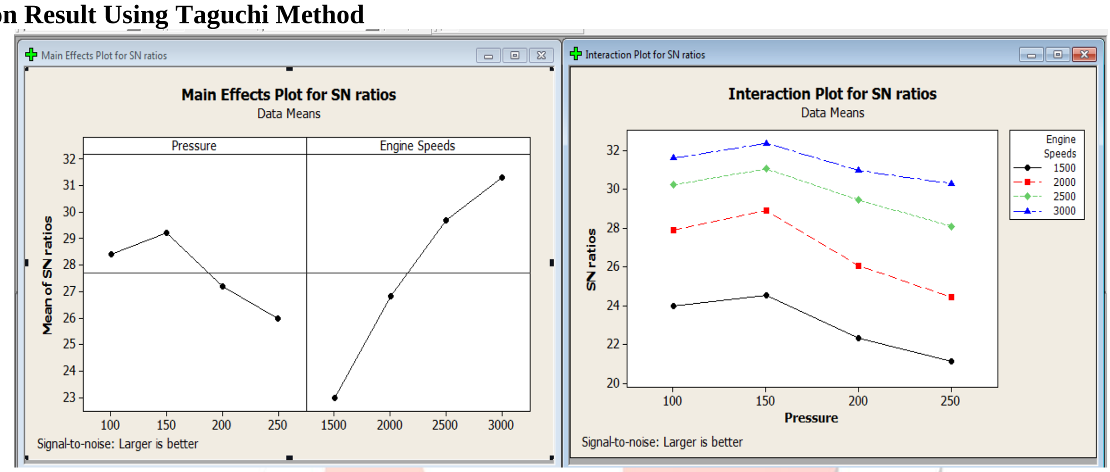


Figure 11: SN Ratios of Power Vs Pressure

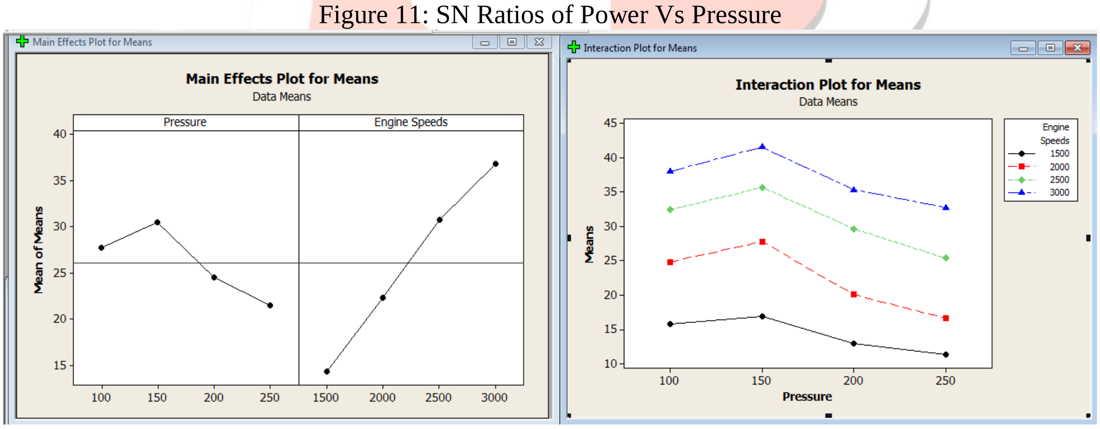


Figure 12: Means of Power Vs Pressure

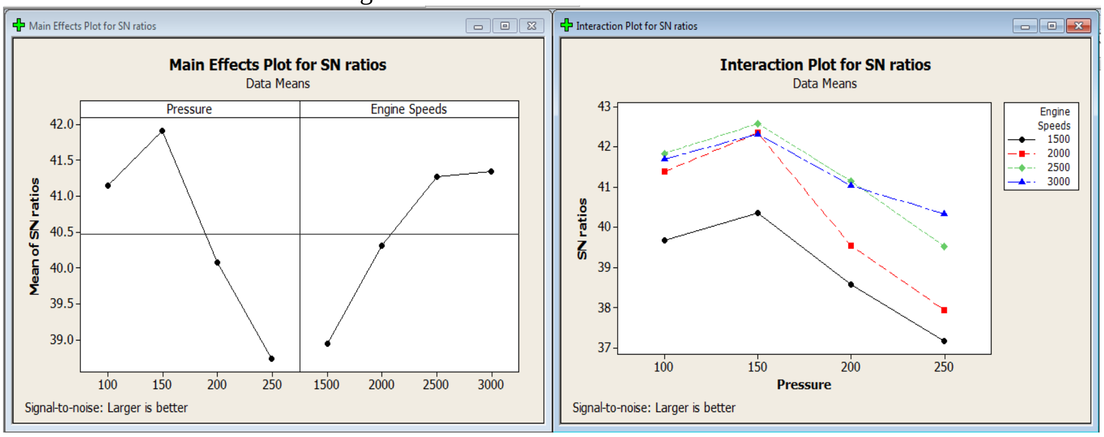


Figure 13: SN Ratios of Torque Vs Pressure

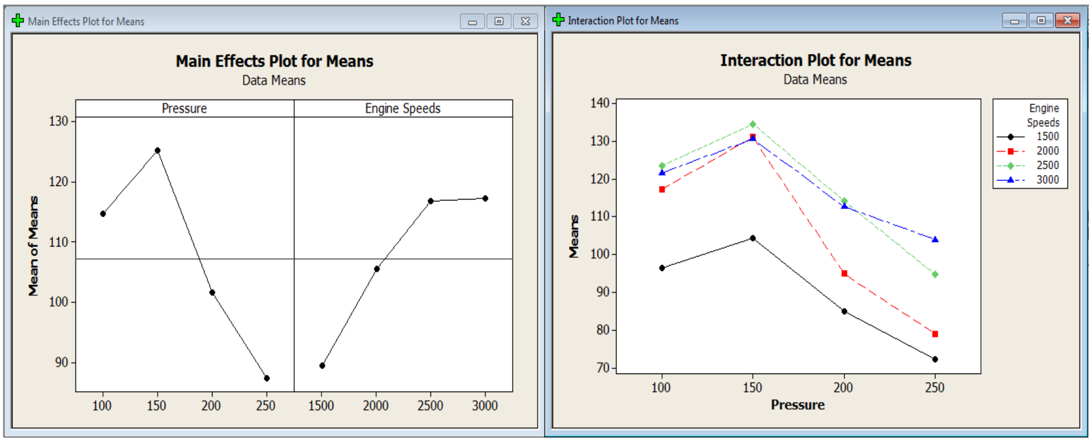


Figure 14: Mean of Torque Vs Pressure

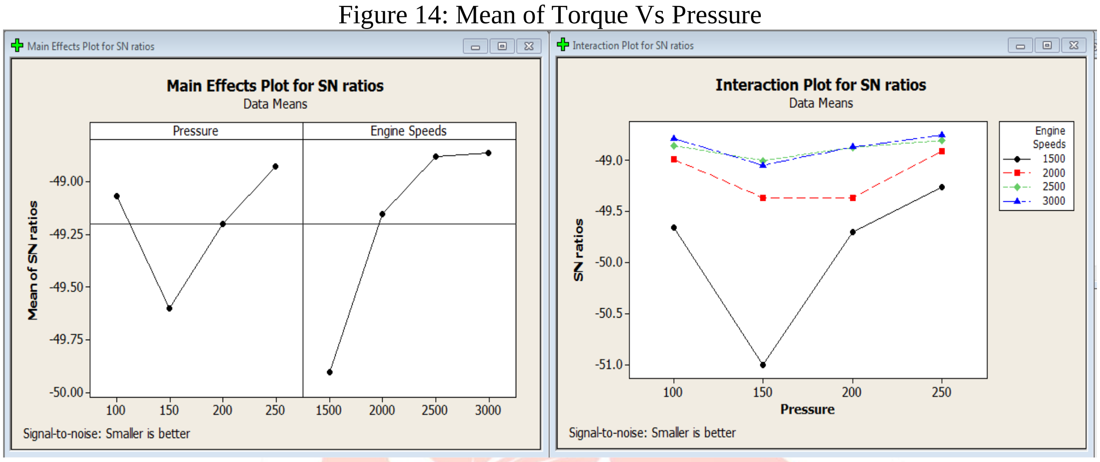


Figure 15: SN Ratios of SFC Vs Pressure

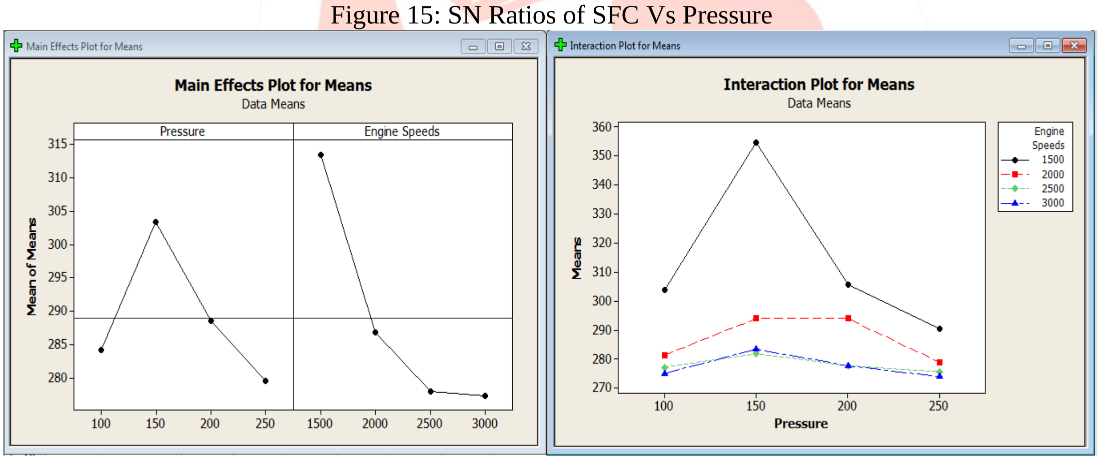


Figure 16: Mean of SFC Vs Pressure

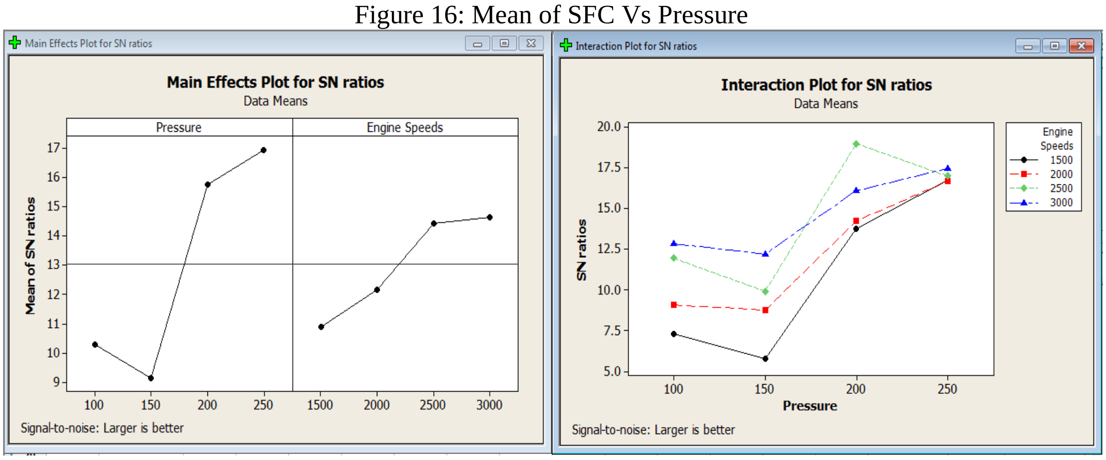


Figure 17: SN Ratios of O_2 Vs Pressure

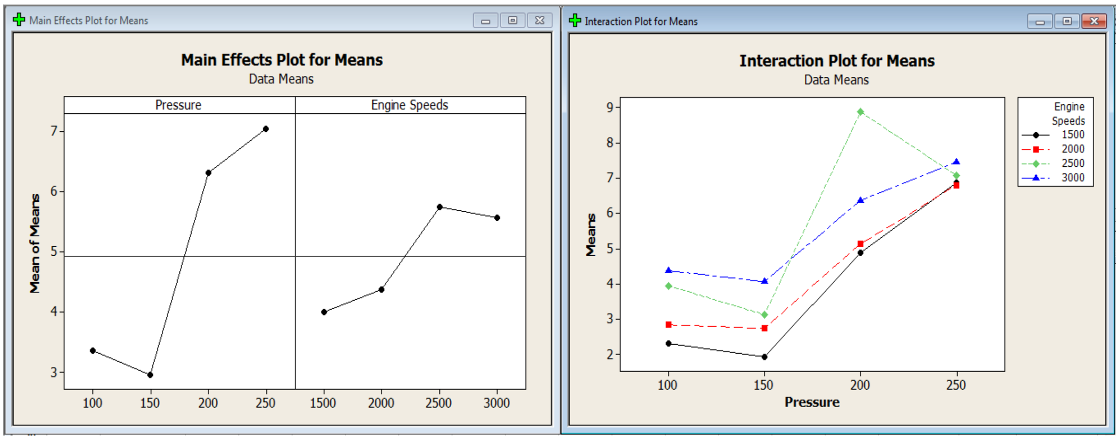


Figure 18: Mean of O_2 Vs Pressure

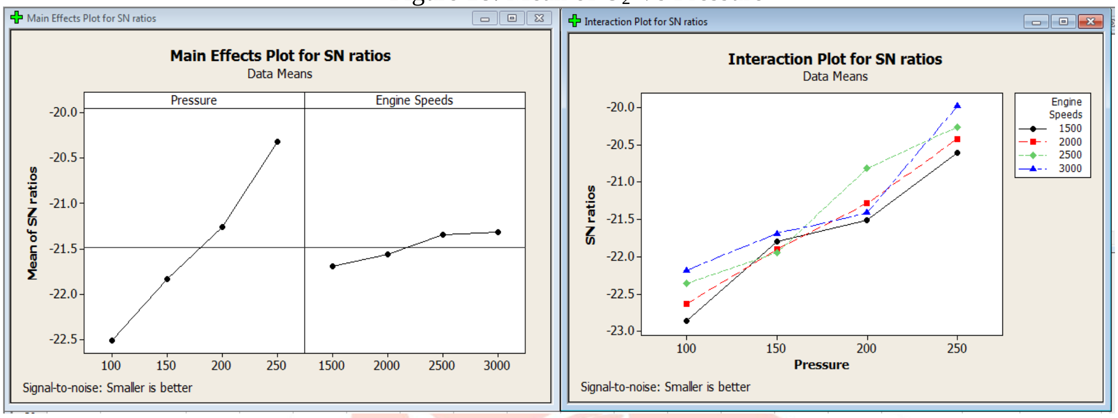


Figure 19: SN Ratios of CO_2 Vs Pressure

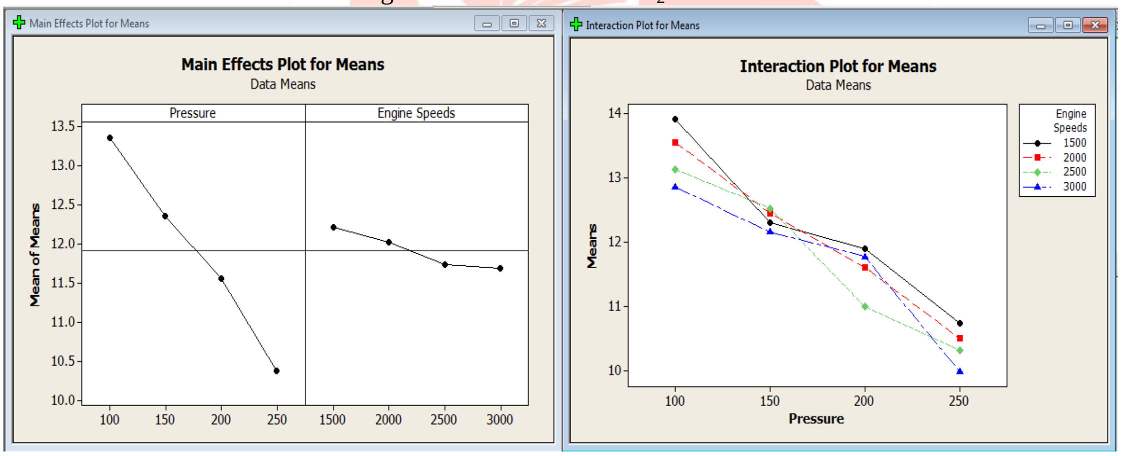


Figure 20: Mean of CO_2 Vs Pressure

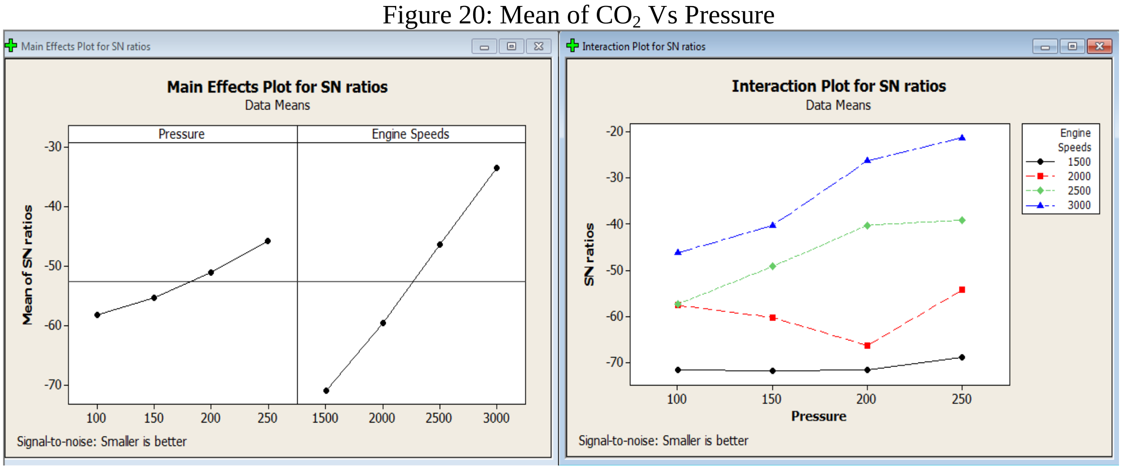


Figure 21: SN Ratios of CO Vs Pressure

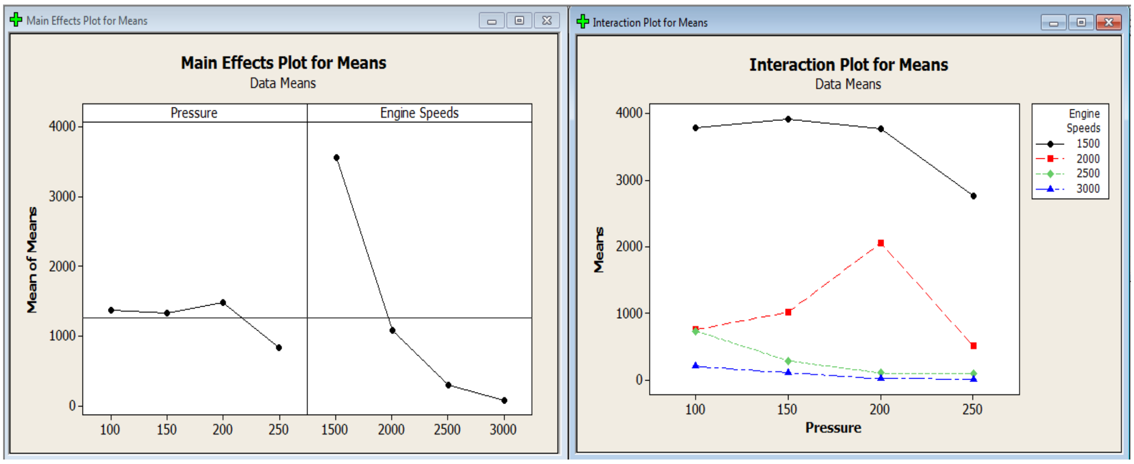


Figure 22: Mean of CO Vs Pressure

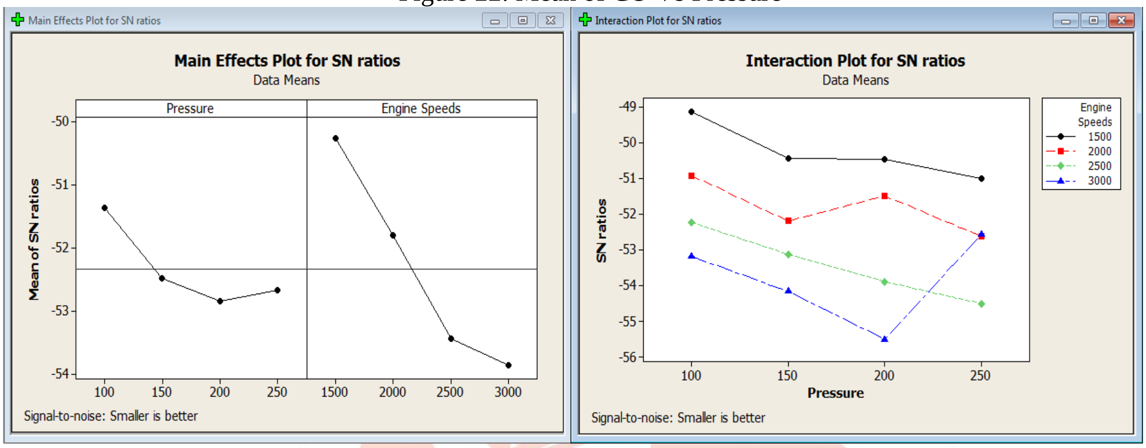


Figure 23: SN Ratios of NO_X Vs Pressure

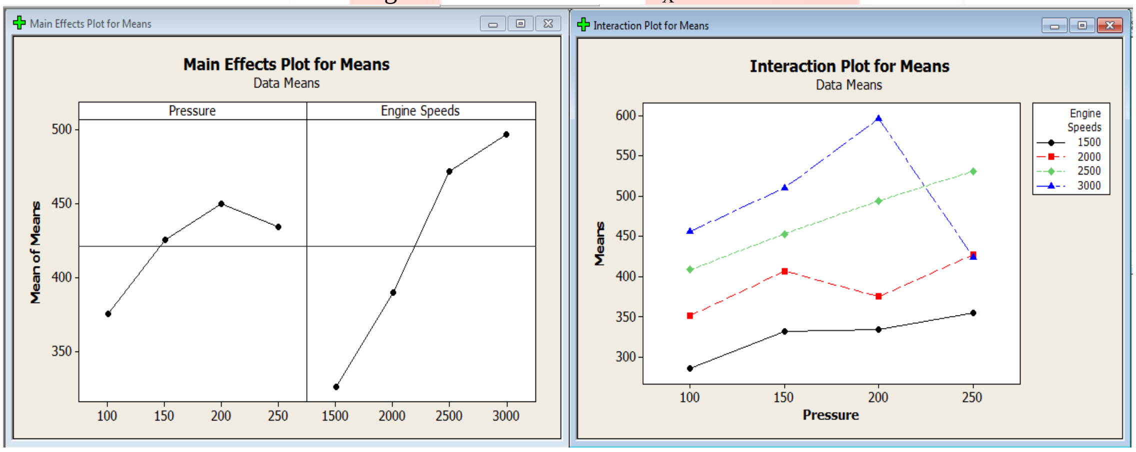


Figure 24: Mean of NO_X Vs Pressure

IV. RESULTS AND DISCUSSION

Figure 4 shows that Maximum engine power was obtained at injection pressure of 150 bar and engine speed of 3000 rpm. Descending order for the power is 150–100–200–250 bar. Figure 5 shows that Maximum engine torque was obtained at injection pressure of 150 bar and engine speed of 2500 rpm. Descending order for the torque is 150–100–200–250 bar. Figure 6 shows that Specific fuel consumption is minimum at 250 bar. Descending order for SFC is 150–200–100–250 bar. Figure 7 shows that O_2 emission descending order is obtained at 250–200–100–150 bar. At 250 bar, the emission has approximately same values for all engine speeds. At 100 and 150 bar the lower engine speed is the lower O_2 emission. Figure 8 shows that CO_2 is reduced when engine speed and injection pressure is increased. High values are obtained at 100 bar. CO_2 emission descending order is obtained at 100–150–200–250 bar. Figure 9 shows that CO is reduced when engine speed is increased. Maximum CO emission is obtained in 1500 rpm at 150 bar and minimum CO values are obtained at 250 bar. Figure 10 shows that NO_X is increased when engine speed is increased. NO_X emission is minimum at 100 bar and maximum at 250 bar.

Figure 11 shows that SN ratio of power is “larger is better”. When pressure is 150 bar then SN ratio of power is maximum at different engine speed and 250 bar SN ratio of power is minimum at different engine speed. Figure 12 shows that mean of power at 150 bar is maximum and mean of power at 250 bar is minimum. When mean of power at 3000 rpm is maximum and mean of power at 1500 rpm is minimum. Figure 13 shows that SN ratio of torque is “larger is better”. When pressure is 150 bar then SN ratio of torque is maximum at different engine speed and 250 bar SN ratio of torque is minimum at different engine speed. Figure 14 shows that mean of torque at 150 bar is maximum and mean of torque at 250 bar is minimum. When mean of torque at 3000 rpm is maximum and mean of torque at 1500 rpm is minimum. Figure 15 shows that SN ratio of SFC is "Smaller is better". When pressure is 150 bar then SN ratio of SFC is smaller at different engine speed and 250 bar SN ratio of SFC is maximum at different engine speed. Figure 16 shows that mean of SFC at 150 bar is maximum and mean of SFC at 250 bar is minimum. When mean of SFC at 3000 rpm is minimum and mean of SFC at 1500 rpm is maximum. Engine speeds increasing with decreasing SFC. Figure 17 shows that SN ratio of O_2 is "larger is better". When pressure is 150 bar then SN ratio of O_2 is minimum at different engine speed and 250 bar SN ratio of O_2 is maximum at different engine speed. Figure 18 shows that mean of O_2 at 150 bar is minimum and mean of O_2 at 250 bar is maximum. When mean of O_2 at 2500 rpm is maximum and mean of O_2 at 1500 rpm is minimum. Figure 19 shows that SN ratio of CO_2 is "Smaller is better". When pressure is 250 bar then SN ratio of CO_2 is maximum at different engine speed and 100 bar SN ratio of CO_2 is minimum at different engine speed. Figure 20 shows that mean of CO_2 at 100 bar is maximum and mean of CO_2 at 250 bar is minimum. When mean of CO_2 at 3000 rpm is minimum and mean of CO_2 at 1500 rpm is maximum. Engine speeds and pressure increasing with decreasing CO_2. Figure 21 shows that SN ratio of CO is "Smaller is better". When pressure is 250 bar then SN ratio of CO is maximum at different engine speed and 100 bar SN ratio of CO is minimum at different engine speed. Engine speeds and pressure increasing with increasing SN ratio of CO. Figure 22 shows that mean of CO at 200 bar is maximum and mean of CO at 250 bar is minimum. When mean of CO at 1500 rpm is maximum and mean of CO at 3000 rpm is minimum. Engine speeds increasing with decreasing CO. Figure 23 shows that SN ratio of NO_X is "Smaller is better". When pressure is 100 bar then SN ratio of NO_X is maximum at different engine speed and 200 bar SN ratio of NO_X is minimum at different engine speed. Figure 24 shows that mean of NO_X at 200 bar is maximum and mean of NO_X at 100 bar is minimum. When mean of NO_X at 3000 rpm is maximum and mean of NO_X at 1500 rpm is minimum. Engine speeds increasing with increasing NO_X.

V. Conclusion

According to results, Using Taguchi Method optimizing injection pressure, the maximum performance has been obtained at 150 bar pressure and 2500 rpm engine speed. In addition, high injection pressure for O_2 and CO_2, low injection pressure for NO_x and smoke level must be preferred for decreasing emissions. The optimal setting of the injection pressure is determined as follows:

Pressure (bar)	**Engine Speed (rpm)**	**Power (KW)**	**Torque (N.m)**	**SFC (g/kwh)**	**O_2 (%)**	**CO_2 (%)**	**CO (ppm)**	**NO_x (ppm)**
150	2500	35.65	134.61	281.77	3.13	12.52	285.71	453.18

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