International Research Journal of Engineering and Technology (IRJET) **e-ISSN: 2395-0056**
Volume: 07 Issue: 07 | July 2020 **www.irjet.net** **p-ISSN: 2395-0072**

Study of Cylinder Deactivation in Camless Heavy-Duty Diesel Engine

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Abstract - *The existing design of the Internal Combustion Engine is at risk of obsolescence due to its high emissions and depletion of fossil fuels. Despite the measures taken to control emissions by introducing various norms, the environment is still impacted. The "Camless Technology" concept, also known as fully variable valve actuation, offers the unique ability to have independent control of the intake and exhaust valves in an Internal Combustion Engine. In an Internal Combustion Engine, the timing, duration, and lift of the valve have a significant impact on engine performance. An engine equipped with a variable valve timing actuation system has different valve timings for different engine speeds and conditions, improving the performance of the engine. To optimize engine performance across the entire operating range, a camless electronically controlled pneumatic/hydraulic valve actuator system is being explored which permits variation in valve lift, duration, and timing. The current technologies which attempted to achieve Variable Valve Timing are still directly or indirectly dependent on the rotation of CAM. Hence, by simulating "Camless Technology" the benefits of having such type of system are demonstrated. Simulation of "Camless Technology" is done using 1-D thermodynamic simulation software. As this technology is operational in passenger vehicles, this project focuses on the Heavy-Duty Diesel Engine which is used in transportation mainly due to their good thermal efficiency. To improve engine performance by constraining the emissions, cylinder deactivation is simulated at part load conditions*.

Key Words: **Camless, Cylinder Deactivation, GT – SUITE, 6 – Cylinder Turbocharged Diesel Engine, Emissions**

1. INTRODUCTION

Cylinder deactivation is used to reduce the fuel consumption and emissions of an internal combustion engine during light-load operation. In typical light-load driving, the driver uses only around 30 percent of an engine's maximum power. In this condition, the engine needs to work to draw air. This causes inefficiency known as pumping loss. The use of cylinder deactivation at light load means there are fewer cylinders drawing air from the intake manifold, which works to increase its fluid (air) pressure. Operation without variable displacement is wasteful because fuel is continuously pumped into each cylinder and combusted even though maximum performance is not required. By shutting down half of an engine's cylinders, the amount of fuel being consumed is much less. Between reducing the pumping losses, which increases pressure in each operating cylinder, and decreasing the amount of fuel being pumped into the cylinders, fuel consumption can be reduced by 8 to 25 percent in highway conditions.

1.1 Advantages

1. Increased fuel efficiency (10-25%)
2. Decreased emissions from deactivated cylinders
3. Better breathing capability of the engine, thereby reducing the power consumed in suction stroke.

1.2 Disadvantages

1. Engine balancing – Deactivating cylinders can cause a change in engine balancing which leads to violent vibration and noises. The way of attaching counter masses to the moving parts like crankshaft is very difficult to calculate and attach the counter masses.
2. The increased cost of manufacturing – Though the deactivation process reduces operation costs, the additional parts like ECM and others will increase the cost of manufacturing.

2. METHODOLOGY FOR CYLINDER DEACTIVATION STRATEGIES

In this study, the strategies to deactivate the cylinders are investigated using a 1-D simulation approach. For this simulation study, there are four conditions of a cylinder deactivation system to be analyzed.

The simulation is executed in Normal mode and deactivated cylinders' modes. There are three conditions of deactivating the cylinders:

a) Cylinder Deactivation Mode (CDA Mode)
b) Intake valves close; Exhaust valves normal
c) Intake valves normal; Exhaust valves close

"Cylinder deactivation" (CDA) mode is when both intake and exhaust valves are switched off. As for the intake valves close; exhaust valves normal, the intake valves are switched off by setting the lift arrays to zero while the exhaust valves run normally and vice versa. All of these modes only affect cylinders 4, 5, and 6. Cylinder 1, 2, and 3 are allowed to operate normally without any modification. The performance output of the engine in normal and CDA mode are evaluated based on engine speed range between 800 to 2200 rpm and at specific engine 25% load condition.

This study is to investigate the strategy of deactivating the cylinder, especially at part load condition. Thus, the engine simulation model is applied to predict engine performance at several fixed variables.

Figure -1: Methodology

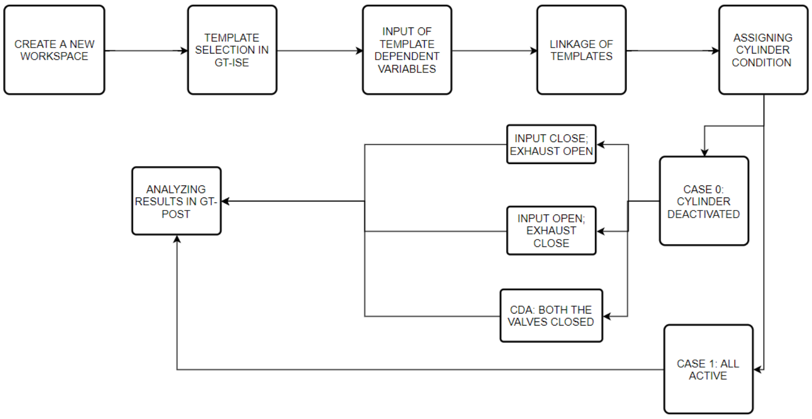
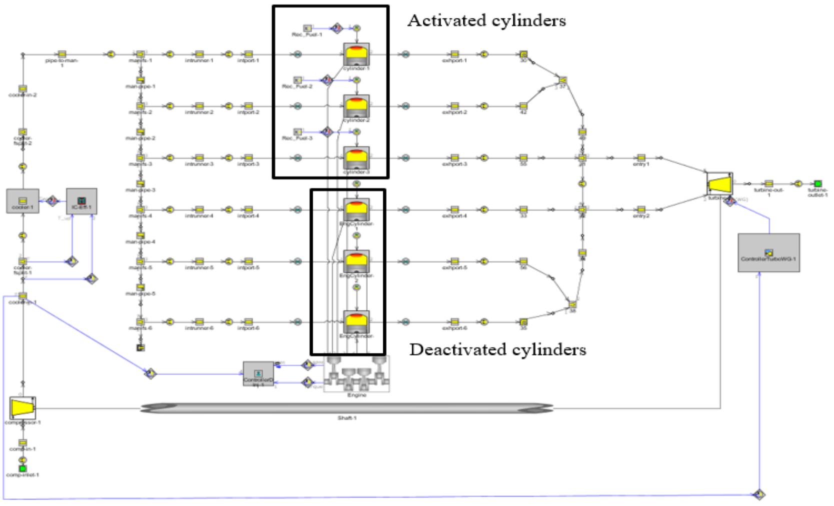


Figure -2: GT-Suite Model for Deactivating Three Cylinders in a 6-Cylinder Engine



3. BOUNDARY CONDITIONS

VARIABLE	VALUE
Inlet Crank Timing Angle	360
Outlet Crank Timing Angle	180
Angle Multiplier for Inlet	1.2694
Angle Multiplier for Exhaust	1.1437
Lift Multiplier for Inlet	1
Lift Multiplier for Exhaust	1

Table -1: Boundary Conditions

The targeted torque by the engine controller are as follows:

RPM	Torque (Nm)
2200	212.5
1800	237.5
1200	250
800	165

Table -2: Targeted Torque

The valve timings followed are as follows:

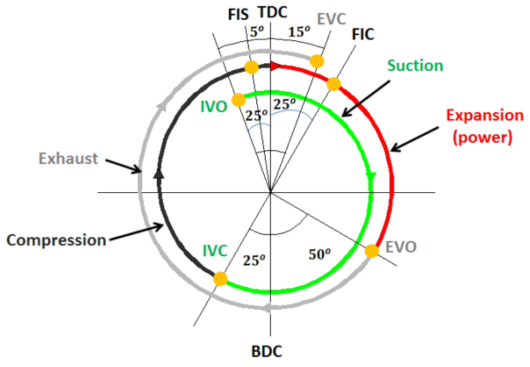


Figure -3: Valve Timings

4. RESULTS

The engine performances for all four modes are as follows:

NORMAL MODE

RPM	BSFC (g/kW-hr)	Pmep (Bar)	Imep (Bar)
2200	266.6	-0.24	6
1800	248.4	-0.11	6.3
1200	236.8	-0.01	6.26
800	249.5	0.00	4.34

EXHAUST OPEN; INLET CLOSE

RPM	BSFC (g/kW-hr)	Pmep (Bar)	Imep (Bar)
2200	250.7	-0.39	5.89
1800	233.4	-0.27	6.23
1200	223.2	-0.23	6.18
800	232.8	-0.28	4.24

INLET OPEN; EXHAUST CLOSE

RPM	BSFC (g/kW-hr)	Pmep (Bar)	Imep (Bar)
2200	429.0	-3.69	6.1
1800	366.2	-2.94	6.39
1200	320.7	-2.06	6.27
800	333.7	-1.67	4.37

CDA

RPM	BSFC (g/kW-hr)	Pmep (Bar)	Imep (Bar)
2200	238.5	-0.03	6.00
1800	224.1	+0.03	6.31
1200	214.2	+0.07	6.26
800	220.1	+0.03	4.31

Table -3: Engine Performance at Various Modes

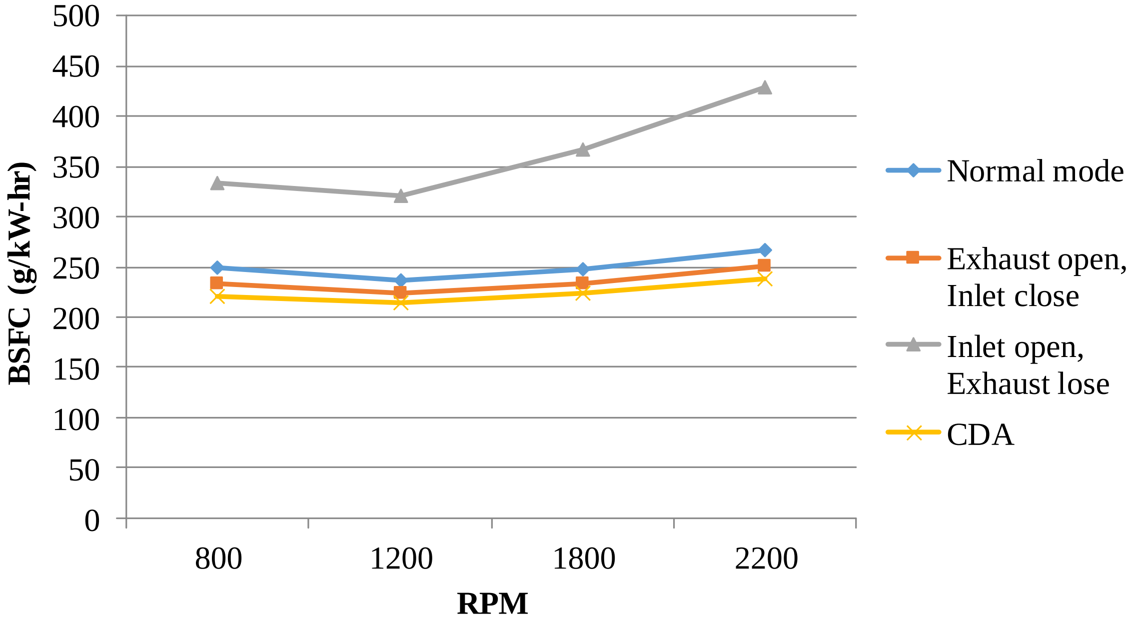


Chart -1: BSFC (g/kW-hr) vs RPM

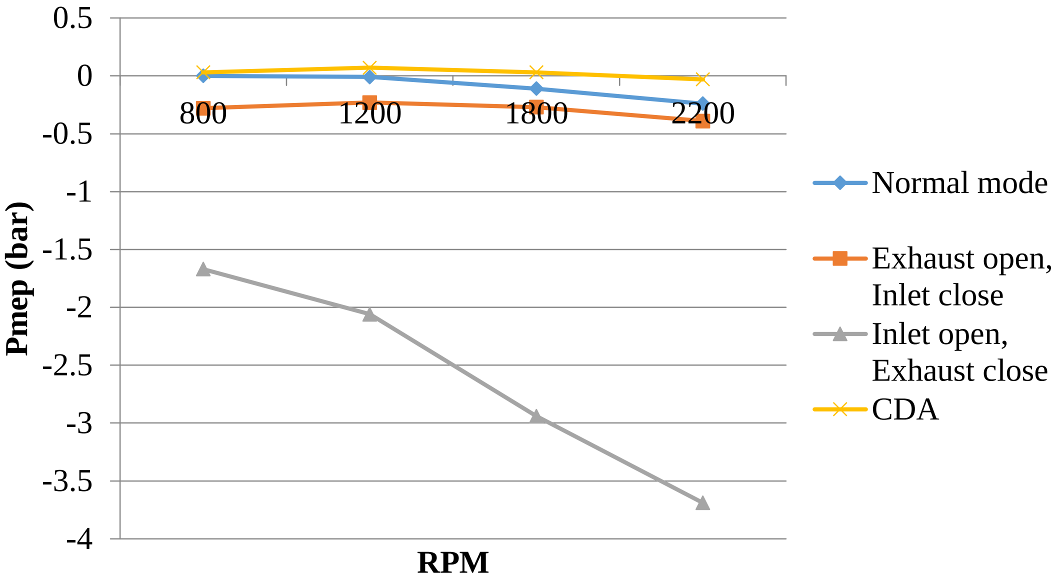


Chart -2: Pmep (bar) vs RPM

The engine model that produces the lowest pumping loss is the CDA mode where the intake and exhaust valves are both closed. By closing the intake and exhaust valves, the trapped air act like pneumatic spring as the piston moves up to compress it. This will reduce the pumping work done by the engine. However, the intake normal; exhaust off mode shows a higher pressure value of PMEP. This indicates that this mode has a high pumping loss. It happens due to the working intake valves in this mode while the exhaust valve is closed. Air is sucked into the cylinder during the intake stroke, adding fresh air to the existing trapped air inside the cylinder that could not escape due to a closed exhaust valve. This caused the pressure in the cylinder to build up and need extra work to compress the air. LogP-LogV diagram is plotted for different modes of engine. All deactivated modes reduce the pumping loss by increasing the pressure in the active cylinders. All the deactivated modes show a significant increase in pressure during compression and power stroke. Overall, most of the deactivated modes show a significant reduction of pumping loss and increase of cylinder pressure for combustion.

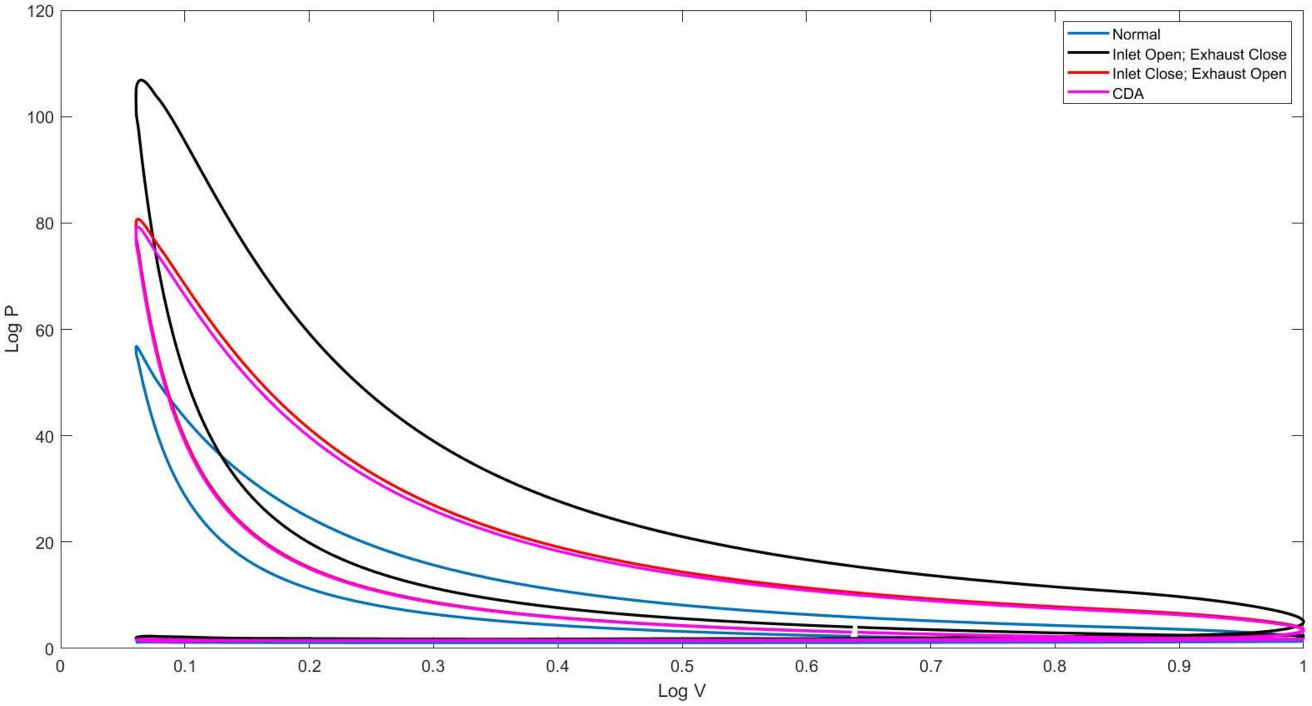


Chart -3: Log Pressure Vs Log Volume

BFSC is an important parameter to identify the fuel efficiency and fuel consumption of the engine. The worst performance in BSFC is when the exhaust valves of the cylinder are switched off while the intake valves operate in normal conditions. This can be related to the very high pumping pressure in the cylinder due to the opening of the intake valve which leads to very high fuel consumption to power the engine.

5. CONCLUSIONS

As for reducing pumping loss or PMEP, the mode that is most effective and suitable is CDA mode where both the intake and exhaust valves are closed. CDA mode also has the lowest BSFC and overall fuel consumption amongst the other engine modes. The following table shows the percentage change in Pmep, Imep, and BSFC from normal to exhaust valve open, inlet valve closed; exhaust valve closed, inlet valve open; and to CDA respectively.

	800 RPM			1200 RPM			1800 RPM			2200 RPM		
Pumping losses (bar)	↑ by 0.28 bar	↑ by 1.67 bar	↓ by 0.03 bar	↑ by 0.22 bar	↑ by 2.05 bar	↓ by 0.06 bar	↑ by 0.16 bar	↑ by 2.83 bar	↓ by 0.14 bar	↑ by 0.15 bar	↑ by 3.45 bar	↓ by 0.21 bar
IMEP (bar)	2.30 % ↓	0.69 % ↑	0.69 % ↓	1.27 % ↓	0.16 % ↑	0%	1.12 % ↓	1.43 % ↑	0.16 % ↑	1.83 % ↓	1.67 % ↑	0%
BSFC (g/kW-h)	6.69 % ↓	33,74 % ↑	11.78 % ↓	5.74 % ↓	35.43 % ↑	9.54 % ↓	6.03 % ↓	47.42 % ↑	9.78 % ↓	5.96 % ↓	60.91 % ↑	10.55 % ↓

🟦 Percentage change from normal to exhaust valve open, inlet valve closed

🟥 Percentage change from normal to exhaust valve closed, inlet valve open

🟩 Percentage change from normal to CDA

Table -4: Engine Performance Comparison

6. EFFECT OF CYLINDER DEACTIVATION AT PART LOAD CONDITIONS

This study is to investigate the strategy of deactivating the cylinder, especially at part load condition. In the previous section, we concluded that “CDA Mode” is the best deactivating strategy. In this section, CDA mode will be compared with Normal Mode at part load conditions and thus the benefits of deactivation will be highlighted.

7. METHODOLOGY FOR CYLINDER DEACTIVATION AT PART LOAD CONDITIONS

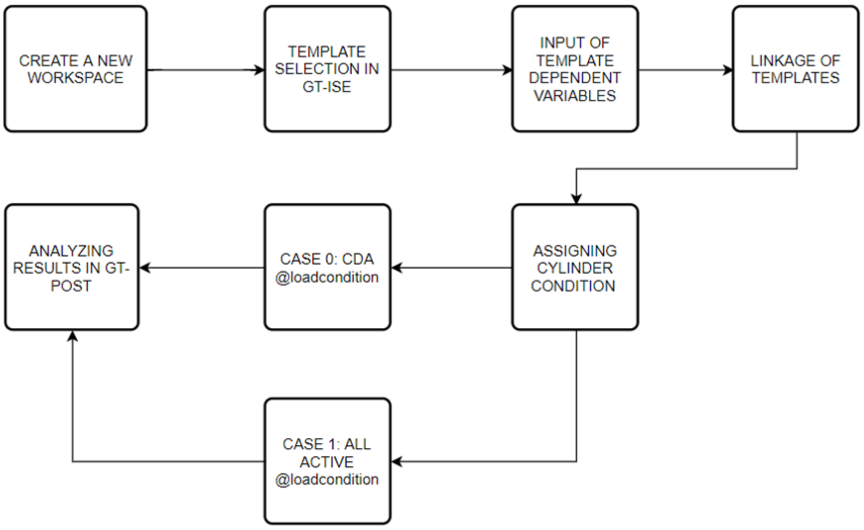


Figure -4: Methodology

Different load conditions, torque is targeted and engine performance variables are compared for CDA and Normal Mode.

8. BOUNDARY CONDITIONS

Loads of 50%, 30% and 10% at 2200, 1800, 1200, 800 rpm are considered for the simulations.

	RPM			
LOAD %	800	1200	1800	2200
50	330	500	475	425
30	198	300	285	255
10	66	100	95	85

Table -5: Targeted Torque Values

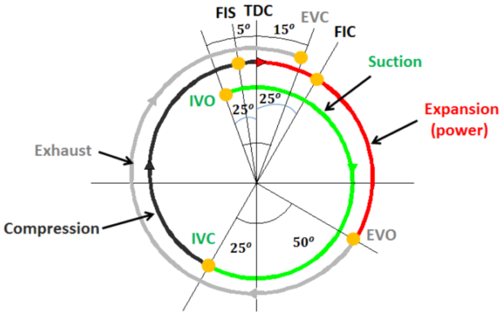


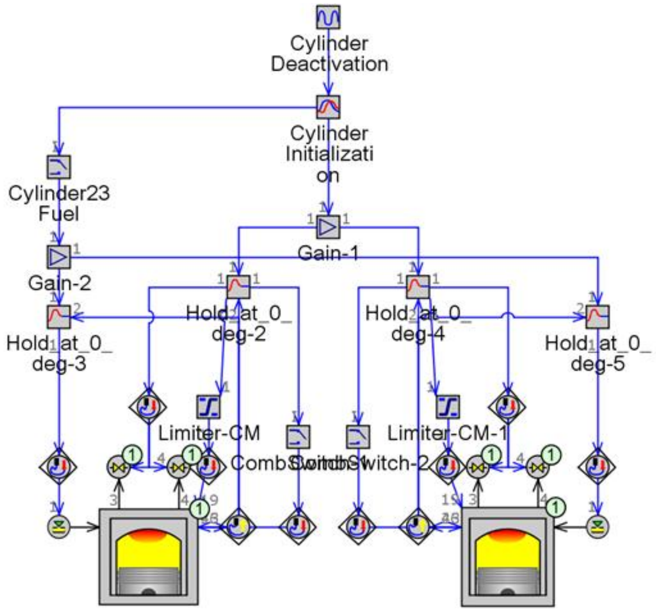
Figure -5: Valve Timings

The following torque values are targeted in both Normal and CDA condition. The aim is to improve engine performance like BSFC, decrease pumping losses and emissions. All of these simulations were carried out with a fixed valve timing.

VARIABLE	VALUE
Inlet Crank Timing Angle	360
Outlet Crank Timing Angle	180
Angle Multiplier for Inlet	1.2694
Angle Multiplier for Exhaust	1.1437
Lift Multiplier for Inlet	1
Lift Multiplier for Exhaust	1

Table -6: Boundary Conditions

Cylinder 1,2,3 are inactive condition whereas cylinders 4, 5, 6 are deactivated. The deactivation is done by manually inputting the Lift Multiplier for both inlet and exhaust as zero. The injected full mass in the deactivated cylinders is also inputted as zero. The overall convection multiplier for the deactivated cylinder is kept to zero for the WoschniGT, heat transfer model. Instead of inputting the multiplier as zero, we can also add a control system that worked electronically and based on the dynamic scenario automatically shifts between normal and CDA mode.



This is a control system that would deactivate the cylinders by an input signal of 0 or 1.

1 stand for all active

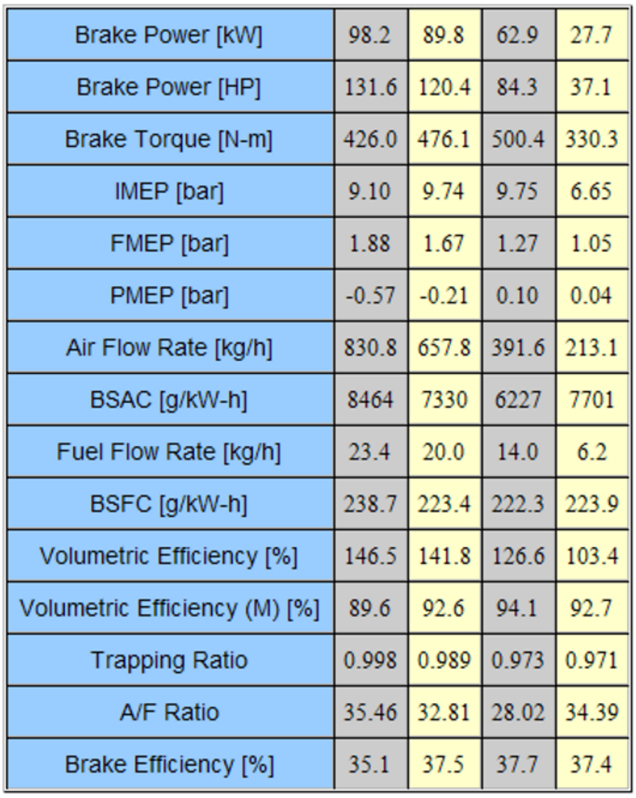
0 stands for CDA

Figure -6: Control System for Cylinder

9. RESULTS

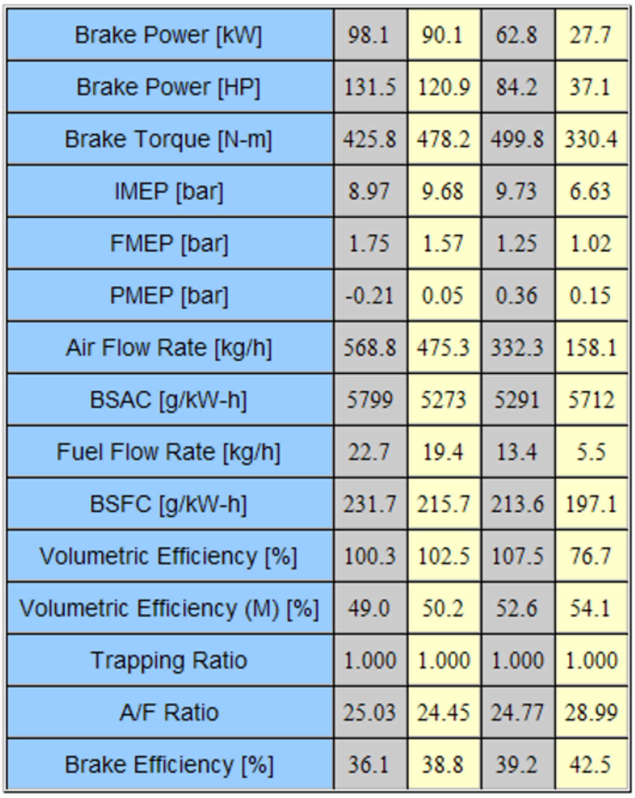
CASE 1: 50% LOAD

After simulating for 50% Load condition, these are the engine performance results.



	1	2	3	4
Brake Power [kW]	98.2	89.8	62.9	27.7
Brake Power [HP]	131.6	120.4	84.3	37.1
Brake Torque [N-m]	426.0	476.1	500.4	330.3
IMEP [bar]	9.10	9.74	9.75	6.65
FMEP [bar]	1.88	1.67	1.27	1.05
PMEP [bar]	-0.57	-0.21	0.10	0.04
Air Flow Rate [kg/h]	830.8	657.8	391.6	213.1
BSAC [g/kW-h]	8464	7330	6227	7701
Fuel Flow Rate [kg/h]	23.4	20.0	14.0	6.2
BSFC [g/kW-h]	238.7	223.4	222.3	223.9
Volumetric Efficiency [%]	146.5	141.8	126.6	103.4
Volumetric Efficiency (M) [%]	89.6	92.6	94.1	92.7
Trapping Ratio	0.998	0.989	0.973	0.971
A/F Ratio	35.46	32.81	28.02	34.39
Brake Efficiency [%]	35.1	37.5	37.7	37.4

Table -7: Engine Performance (VVT)



	1	2	3	4
Brake Power [kW]	98.1	90.1	62.8	27.7
Brake Power [HP]	131.5	120.9	84.2	37.1
Brake Torque [N-m]	425.8	478.2	499.8	330.4
IMEP [bar]	8.97	9.68	9.73	6.63
FMEP [bar]	1.75	1.57	1.25	1.02
PMEP [bar]	-0.21	0.05	0.36	0.15
Air Flow Rate [kg/h]	568.8	475.3	332.3	158.1
BSAC [g/kW-h]	5799	5273	5291	5712
Fuel Flow Rate [kg/h]	22.7	19.4	13.4	5.5
BSFC [g/kW-h]	231.7	215.7	213.6	197.1
Volumetric Efficiency [%]	100.3	102.5	107.5	76.7
Volumetric Efficiency (M) [%]	49.0	50.2	52.6	54.1
Trapping Ratio	1.000	1.000	1.000	1.000
A/F Ratio	25.03	24.45	24.77	28.99
Brake Efficiency [%]	36.1	38.8	39.2	42.5

Table -8: Engine Performance (CDA)

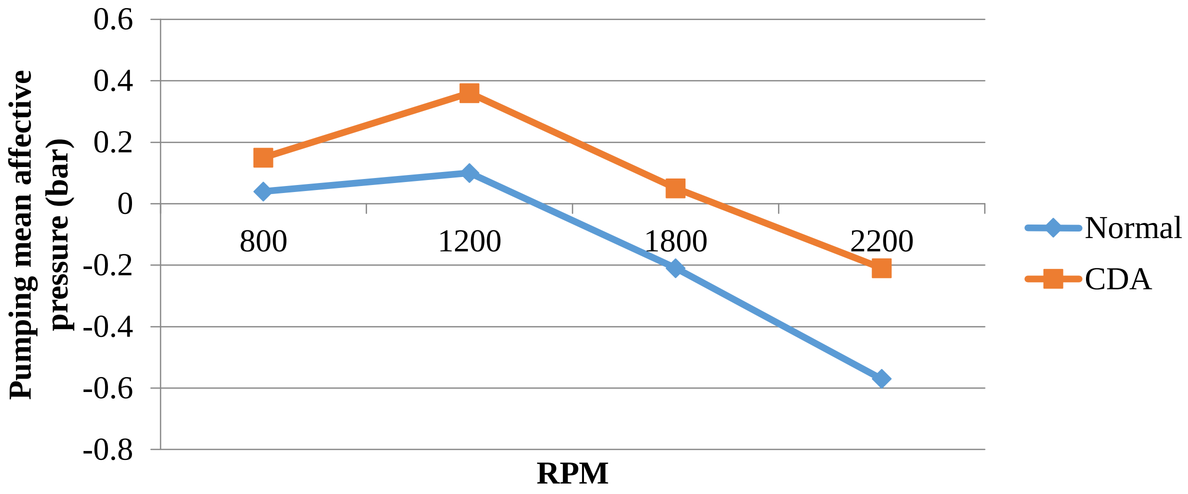


Chart -4: Pmep vs RPM

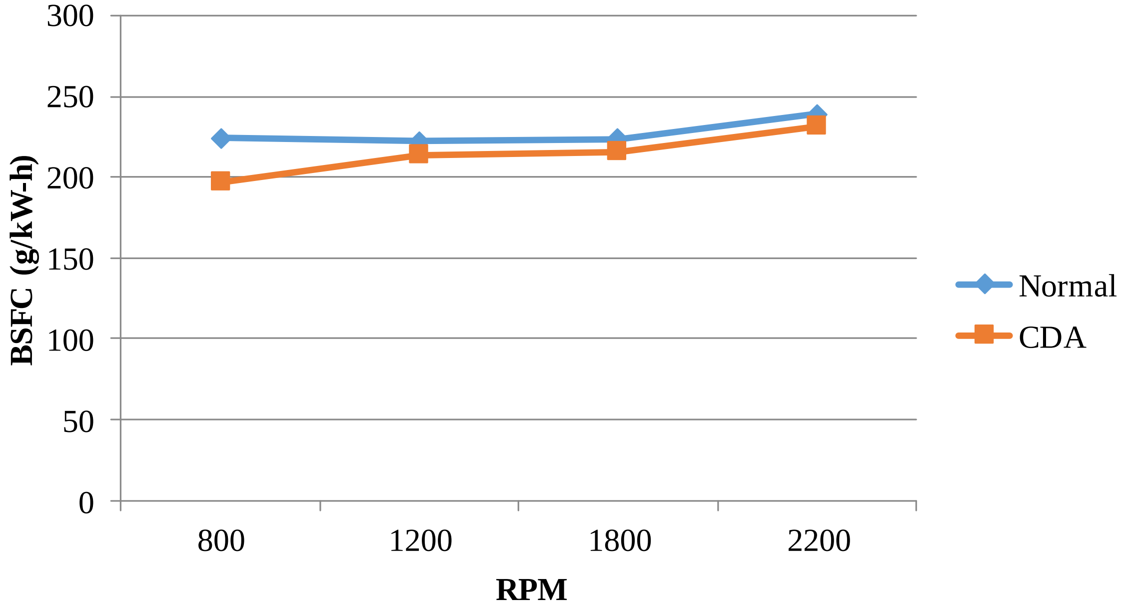


Chart -5: BSFC vs RPM

The Brake Power is constant at respective RPMs. There was an improvement in BSFC and pumping losses for all the RPMs.

RPM	Total NOx (Normal)	Total NOx (CDA)
2200	12156	7095
1800	13608	7896
1200	12570	6435
800	13896	9642

Table -9: NOx for various RPM

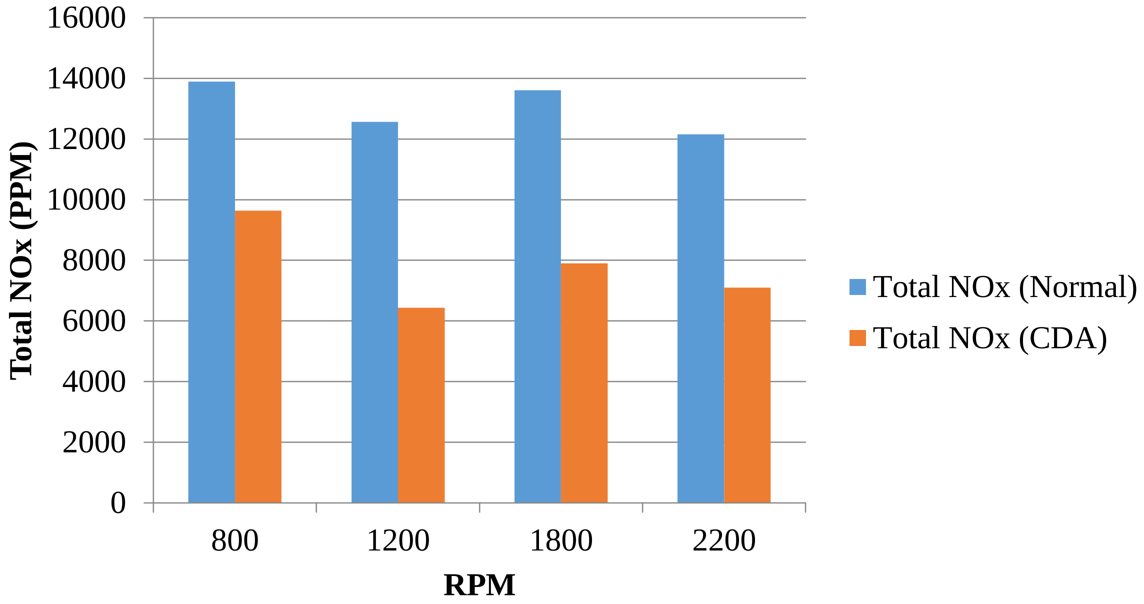
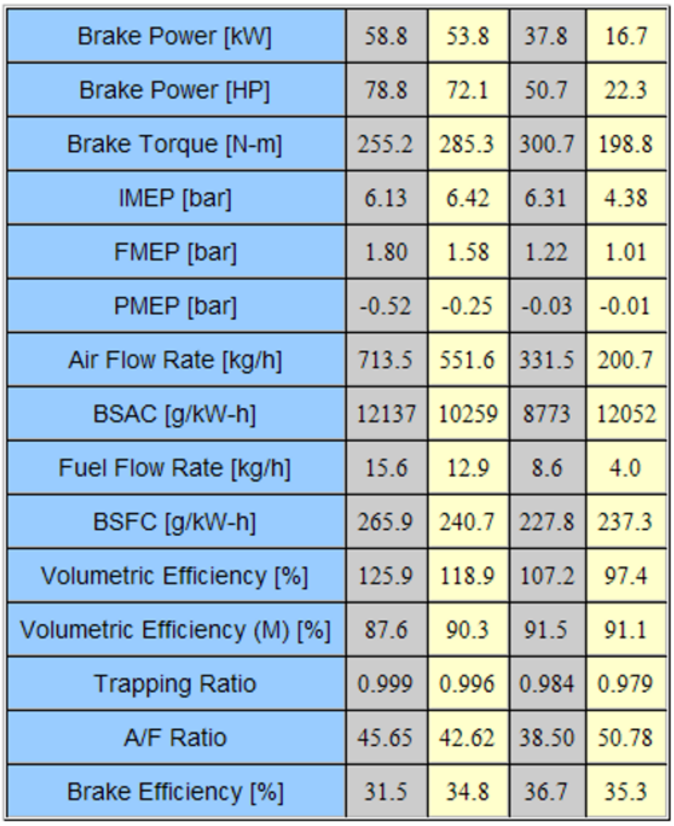


Chart -6: Total NOx vs RPM

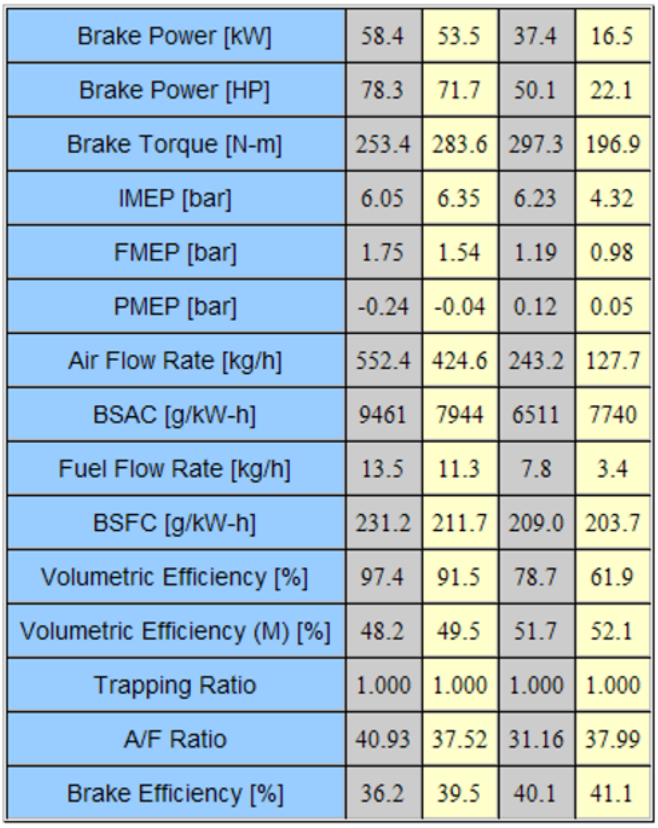
CASE 2: 30% LOAD

After simulating for 30% Load condition, these are the engine performance results.



	1	2	3	4
Brake Power [kW]	58.8	53.8	37.8	16.7
Brake Power [HP]	78.8	72.1	50.7	22.3
Brake Torque [N-m]	255.2	285.3	300.7	198.8
IMEP [bar]	6.13	6.42	6.31	4.38
FMEP [bar]	1.80	1.58	1.22	1.01
PMEP [bar]	-0.52	-0.25	-0.03	-0.01
Air Flow Rate [kg/h]	713.5	551.6	331.5	200.7
BSAC [g/kW-h]	12137	10259	8773	12052
Fuel Flow Rate [kg/h]	15.6	12.9	8.6	4.0
BSFC [g/kW-h]	265.9	240.7	227.8	237.3
Volumetric Efficiency [%]	125.9	118.9	107.2	97.4
Volumetric Efficiency (M) [%]	87.6	90.3	91.5	91.1
Trapping Ratio	0.999	0.996	0.984	0.979
A/F Ratio	45.65	42.62	38.50	50.78
Brake Efficiency [%]	31.5	34.8	36.7	35.3

Table -10: Engine Performance (VVT)



	1	2	3	4
Brake Power [kW]	58.4	53.5	37.4	16.5
Brake Power [HP]	78.3	71.7	50.1	22.1
Brake Torque [N-m]	253.4	283.6	297.3	196.9
IMEP [bar]	6.05	6.35	6.23	4.32
FMEP [bar]	1.75	1.54	1.19	0.98
PMEP [bar]	-0.24	-0.04	0.12	0.05
Air Flow Rate [kg/h]	552.4	424.6	243.2	127.7
BSAC [g/kW-h]	9461	7944	6511	7740
Fuel Flow Rate [kg/h]	13.5	11.3	7.8	3.4
BSFC [g/kW-h]	231.2	211.7	209.0	203.7
Volumetric Efficiency [%]	97.4	91.5	78.7	61.9
Volumetric Efficiency (M) [%]	48.2	49.5	51.7	52.1
Trapping Ratio	1.000	1.000	1.000	1.000
A/F Ratio	40.93	37.52	31.16	37.99
Brake Efficiency [%]	36.2	39.5	40.1	41.1

Table -11: Engine Performance (CDA)

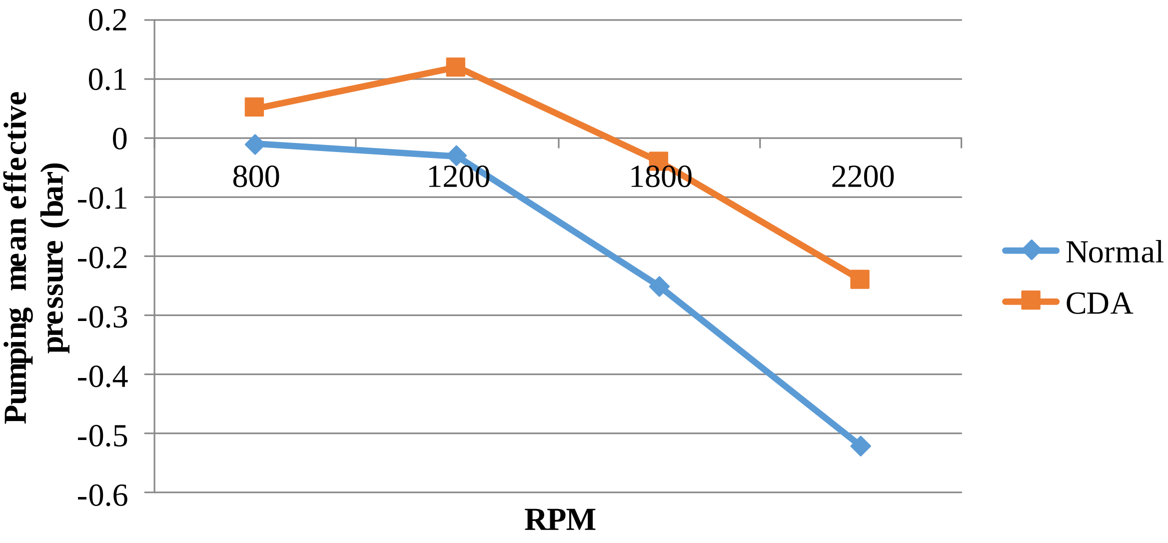


Chart -7: Pmep vs RPM

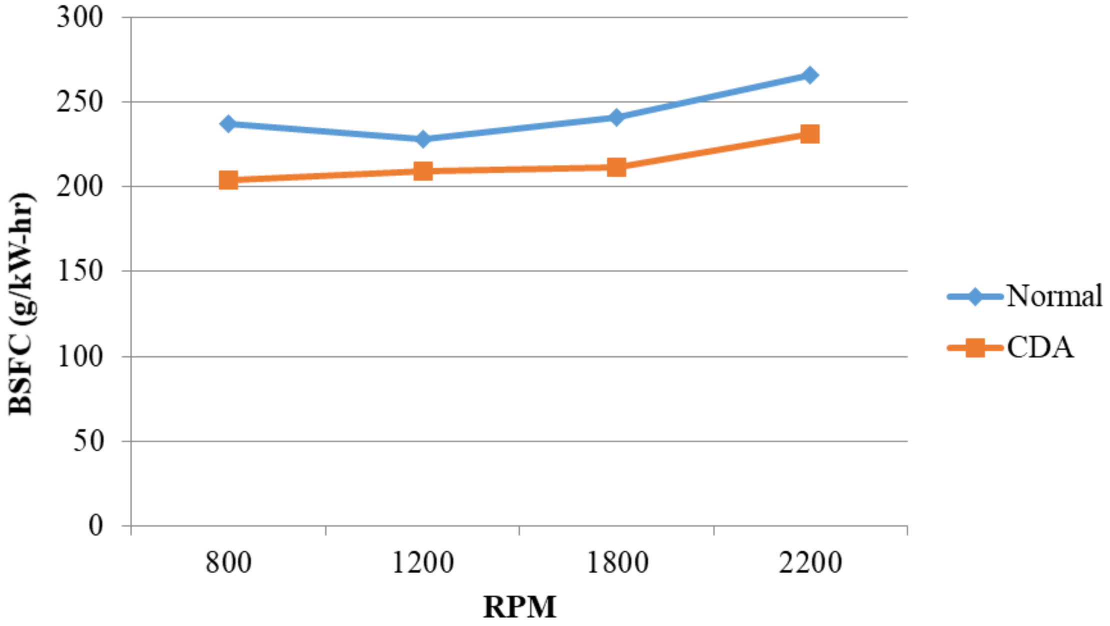


Chart -8: BSFC vs RPM

The Brake Power is constant at respective RPMs. There was an improvement in BSFC and pumping losses for all the RPMs.

RPM	Total NOx (Normal)	Total NOx (CDA)
2200	9492	4965
1800	10170	5667
1200	9852	6438
800	7980	7044

Table -12: NOx for various RPM

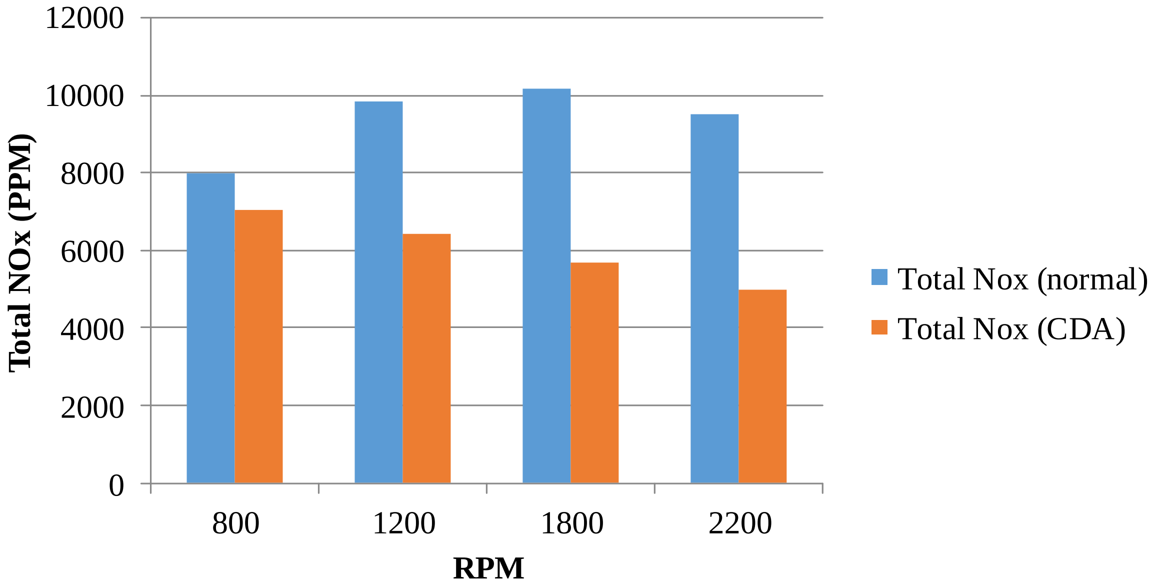
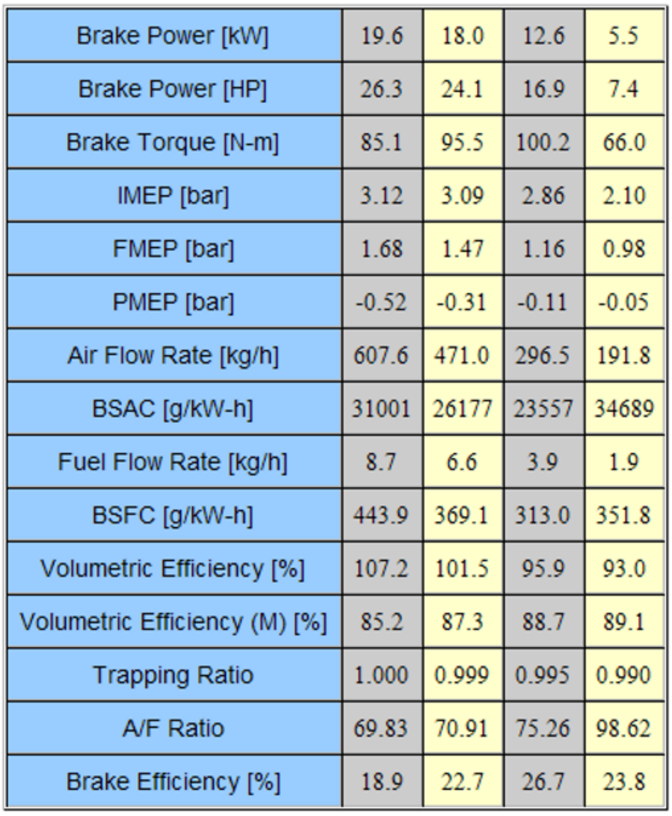


Chart -9: Total NOx vs RPM

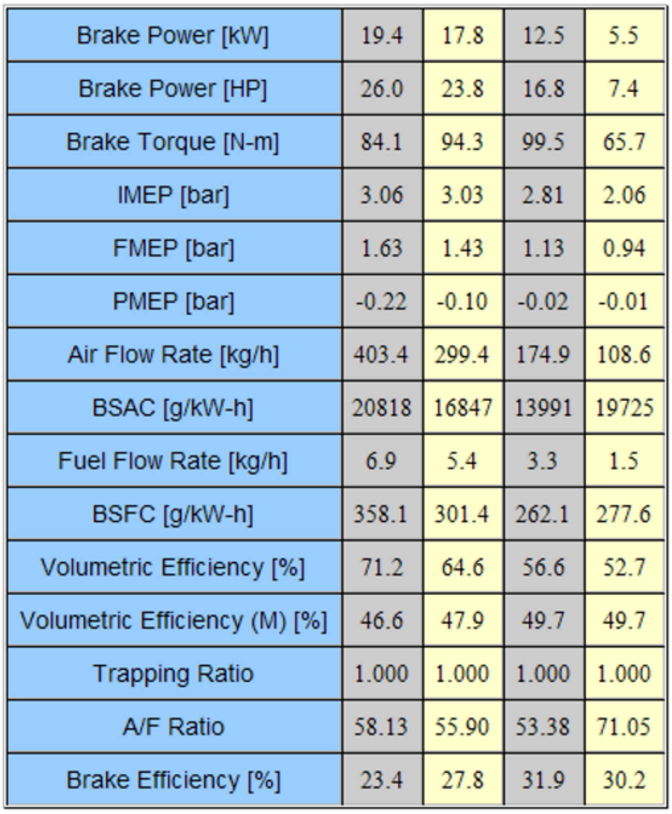
CASE 3: 10% LOAD

After simulating for 10% Load condition, these are the engine performance results.



	1	2	3	4
Brake Power [kW]	19.6	18.0	12.6	5.5
Brake Power [HP]	26.3	24.1	16.9	7.4
Brake Torque [N-m]	85.1	95.5	100.2	66.0
IMEP [bar]	3.12	3.09	2.86	2.10
FMEP [bar]	1.68	1.47	1.16	0.98
PMEP [bar]	-0.52	-0.31	-0.11	-0.05
Air Flow Rate [kg/h]	607.6	471.0	296.5	191.8
BSAC [g/kW-h]	31001	26177	23557	34689
Fuel Flow Rate [kg/h]	8.7	6.6	3.9	1.9
BSFC [g/kW-h]	443.9	369.1	313.0	351.8
Volumetric Efficiency [%]	107.2	101.5	95.9	93.0
Volumetric Efficiency (M) [%]	85.2	87.3	88.7	89.1
Trapping Ratio	1.000	0.999	0.995	0.990
A/F Ratio	69.83	70.91	75.26	98.62
Brake Efficiency [%]	18.9	22.7	26.7	23.8

Table -13: Engine Performance (VVT)



	1	2	3	4
Brake Power [kW]	19.4	17.8	12.5	5.5
Brake Power [HP]	26.0	23.8	16.8	7.4
Brake Torque [N-m]	84.1	94.3	99.5	65.7
IMEP [bar]	3.06	3.03	2.81	2.06
FMEP [bar]	1.63	1.43	1.13	0.94
PMEP [bar]	-0.22	-0.10	-0.02	-0.01
Air Flow Rate [kg/h]	403.4	299.4	174.9	108.6
BSAC [g/kW-h]	20818	16847	13991	19725
Fuel Flow Rate [kg/h]	6.9	5.4	3.3	1.5
BSFC [g/kW-h]	358.1	301.4	262.1	277.6
Volumetric Efficiency [%]	71.2	64.6	56.6	52.7
Volumetric Efficiency (M) [%]	46.6	47.9	49.7	49.7
Trapping Ratio	1.000	1.000	1.000	1.000
A/F Ratio	58.13	55.90	53.38	71.05
Brake Efficiency [%]	23.4	27.8	31.9	30.2

Table -14: Engine Performance (CDA)

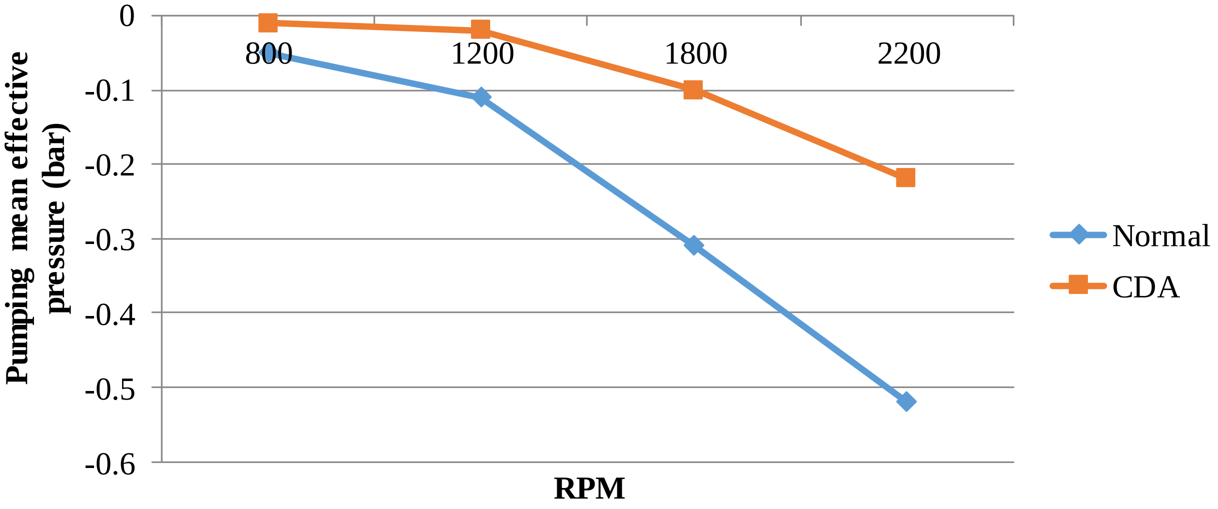


Chart -10: Pmep vs RPM

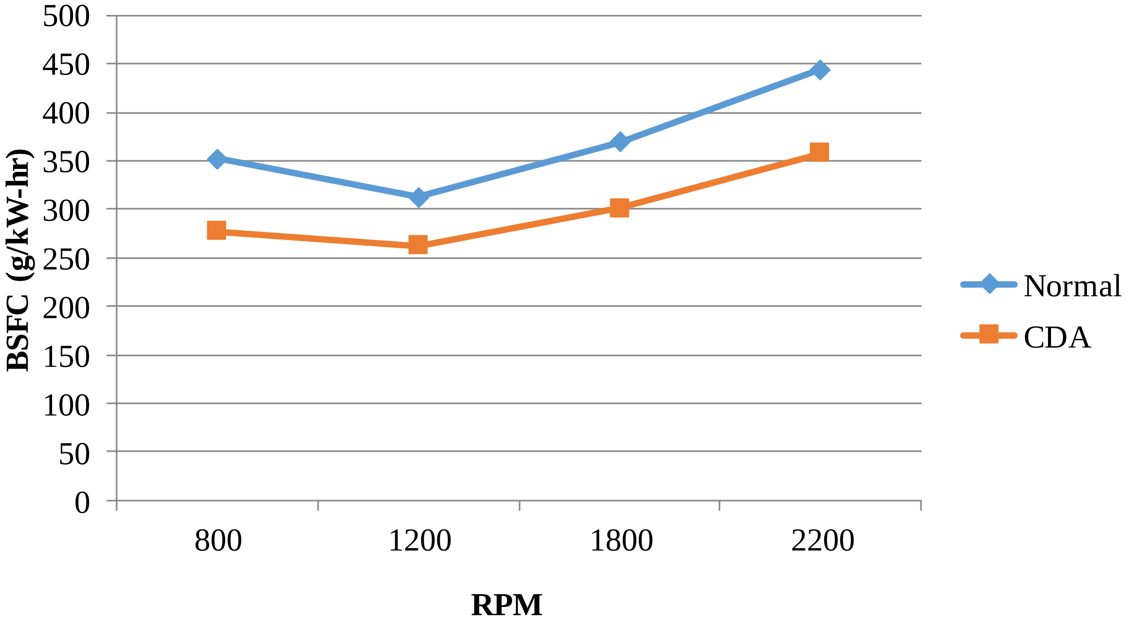


Chart -11: BSFC vs RPM

The Brake Power is constant at respective RPMs. There was an improvement in BSFC and pumping losses for all the RPMs.

RPM	Total NOx (Normal)	Total NOx (CDA)
2200	4116	2688
1800	4344	2928
1200	3780	3198
800	3150	2388

Table -15: NOx for various RPM

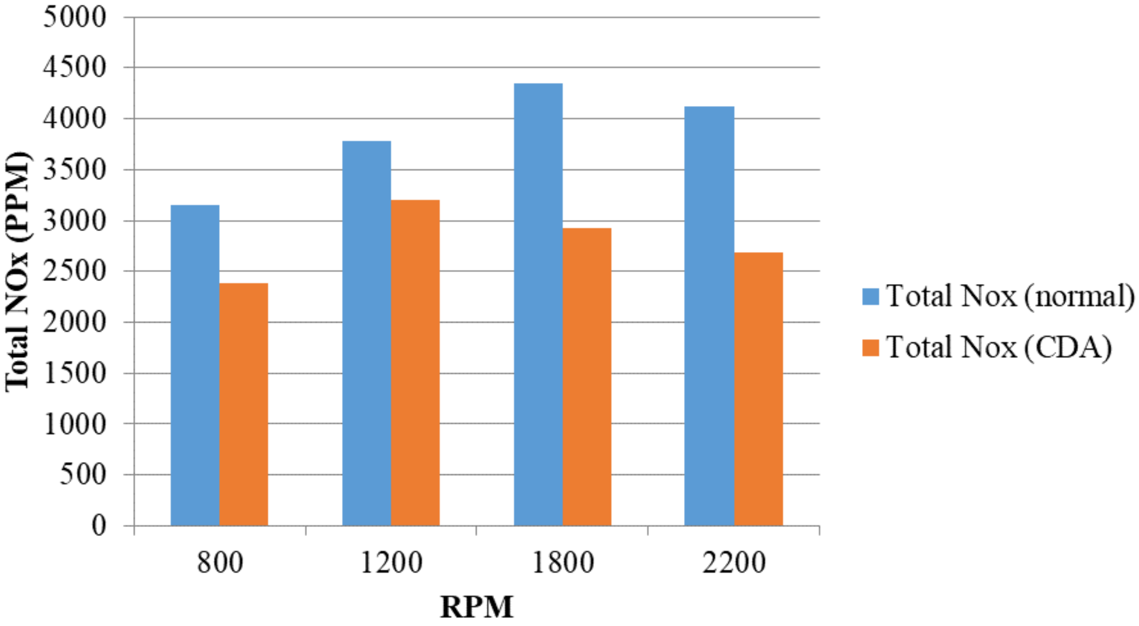


Chart -12: Total NOx vs RPM

The emissions have been reduced by deactivating the cylinders. In the graphs below, we conclude that CDA mode is beneficial for improving engine performance at low load conditions.

Fueling cut-off in the deactivated cylinders can improve fuel economy because it increases the fueling in the firing cylinders so that an appropriate air-fuel ratio can be maintained for better performance. The pumping loss is reduced due to the lower exhaust manifold pressure caused by the drastically reduced engine airflow rate flowing through the given turbine area. The reduction in airflow rate is caused by the reduced effective engine displacement. Only 3 cylinders are functioning which results in lower NOx.

10. CONCLUSIONS

1. Computer simulation techniques are applied to obtain a better understanding in terms of cylinder deactivation technology on engine performance. Reducing pumping loss or PMEP, the mode that is most effective and suitable is CDA mode where both the intake and exhaust valves are closed.

2. CDA mode also has the lowest BSFC and overall fuel consumption amongst the other engine modes. After treatment thermal management in modern diesel engines is a difficult challenge during low-load operation.

3. One of the most significant challenges is maintaining effective after-treatment temperatures. Fuel efficiency is often sacrificed to slow the cooling-off after treatment components during low-load operation. CDA can slow the cooling-off after treatment components in a more fuel-efficient manner through reduced exhaust flow and increased exhaust temperatures.

4. The following tables show the percentage change in pumping losses and BSFC when the design is changed from normal to CDA.

CASE 1: 50% LOAD

Performance Criteria	**800 RPM**	**1200 RPM**	**1800 RPM**	**2200 RPM**
Pumping losses (bar)	↓ by 0.11 bar	↓ by 0.26 bar	↓ by 0.26 bar	↓ by 0.36 bar
BSFC (g/kW-h)	11.96 % ↓	3.91 % ↓	3.44 % ↓	2.93 % ↓
NOx (PPM)	30.61 % ↓	48.80 % ↓	41.97 % ↓	41.63 % ↓

CASE 2: 30% LOAD

Performance Criteria	**800 RPM**	**1200 RPM**	**1800 RPM**	**2200 RPM**
Pumping losses (bar)	↓ by 0.06 bar	↓ by 0.15 bar	↓ by 0.21 bar	↓ by 0.28 bar
BSFC (g/kW-h)	14.15 % ↓	8.25 % ↓	12.04 % ↓	13.05 % ↓
NOx (PPM)	11.73 % ↓	34.65 % ↓	44.27 % ↓	47.69 % ↓

CASE 3: 10% LOAD

Performance Criteria	**800 RPM**	**1200 RPM**	**1800 RPM**	**2200 RPM**
Pumping losses (bar)	↓ by 0.04 bar	↓ by 0.09 bar	↓ by 0.21 bar	↓ by 0.3 bar
BSFC (g/kW-h)	21.09 % ↓	16.26 % ↓	18.34 % ↓	19.32 % ↓
NOx (PPM)	24.19 % ↓	15.39 % ↓	32.59 % ↓	34.69 % ↓

Table -16: Engine Parameters Comparison

REFERENCES

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