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Effects of spark plug configuration on combustion and emission characteristics of a LPG fuelled lean burn SI engine

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Abstract: Introduction of technological innovation in automotive engines in reducing pollution and increasing efficiency have been under contemplation. Gaseous fuels have proved to be a promising way to reduce emissions in Spark Ignition (SI) engines. In particular, LPG settled to be a favourable fuel for SI engines because of their higher hydrogen to carbon ratio, octane rating and lower emissions. Wide ignition limits and efficient combustion characteristics make LPG suitable for lean burn operation. But lean combustion technology has certain drawbacks like poor flame propagation, cyclic variations etc. Based on copious research it was found that location, types and number of spark plug significantly influence in reducing cyclic variations. In this work the influence of single and dual spark plugs of conventional and surface discharge electrode type were analysed. Dual surface discharge electrode spark plug enhanced the brake thermal efficiency and greatly reduced the cyclic variations. The experimental results show that rate of heat release and pressure rise was more and combustion duration was shortened in this configuration. On the emissions front, the NOx emission has increased whereas HC and CO emissions were reduced under lean condition.

1. Introduction

The global crisis of energy is at its peak as the consumption of fossil fuels is increasing day by day, the scientists and researchers are working hard for the finding alternate sources of energies as the fossil fuels are depleting at a very faster rate. Automobiles are crucial consumers of energy in the form of conventional fuels and also pollute the environment with exhaust emissions. Investigation on alternate fuels like CNG (Compressed Natural Gas), LPG (liquefied Petroleum Gas), biogas, hydrogen and producer gas for large scale use as fuel for automotive engines are being conceded as the only alternate solution to preserve the fossil fuel reserves for the future generation. LPG has been used as a substitute for a longer period as domestic and industrial fuel. Off late use of LPG for automotive use is finding interest because of its favorable properties and well established distribution infrastructure. LPG is obtained during natural gas extraction and also from refining of crude oil. LPG main constituents are propane and butane in various proportions. In particular, LPG settled to be a favourable fuel for SI engines because of their higher octane rating, efficient combustion characteristics and lower emissions. In comparison to other gaseous fuel LPG also high flame speed, lower calorific value, density. Using LPG to displace gasoline, diesel can therefore simultaneously realise environmental and economic benefits [1]. Hydrogen to carbon ratio and wide ignition limits makes LPG suitable for lean burn operation. But lean combustion technology has certain drawbacks including flame propagation, cyclic variations etc. The Cyclic variations in the combustion process are important for two reasons .First optimum spark timing is set for average cycles, faster than average cycles have effectively over advanced spark timing and slower cycles have retarded timing, so losses in power and efficiency. Second they are limiting engine operating conditions. Researchers have find out main causes behind cyclic variations i.e. The variation in gas motion in the cylinder during combustion, cycle by cycle, the variation in amount of air and fuel supplied to cylinder in each cycle, variation in mixture composition within the cylinder each cycle specially near spark plug due to variations in mixing between air, fuel, recycled exhaust gas and residual gas [8]. Also with the in-cylinder charge motions including turbulence intensity, mean flow speed and direction at spark plug, A/F ratio at spark plug and in the chamber, variation in residual gas at spark plug and in the chamber, variations in spark discharge characteristics (breakdown energy, timing, type of spark plug and spark orientation), leakage through valves and crevice effects.[10]

Causes of cyclic variations can be divided into two groups: prior-cycle effects (residual gas, etc., results of misfire and partial burn) and same-cycle effects (in cylinder flow, etc., results of random variations. The following could be taken into account for reducing the cyclic variations sparkplug location, spark plug type, orientation of Ground Electrode, number of sparkplugs (multiple spark plugs), addition of hydrogen, control spark timing, valve shrouding, and combustion chamber geometry. It is obtained that the twin-spark configurations give better performances and fuel economy than single-spark arrangement for all spark plug locations excluding centrally located single-spark plug arrangement [12].

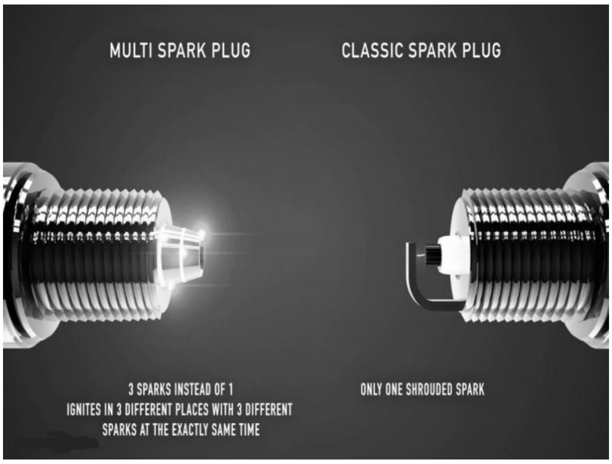

Figure 1. Comparison of SD Spark plug Vs Normal Spark plug [28]

Some investigations found that fast burn can be achievable by dual-spark plug ignition, and lean limits of stable operation can be extended to leaner one. In other investigations DTSI digital twin Spark Ignition which is based on dual spark plug mounted in cylinder head at diametrically opposite to each other simultaneously igniting the charge .Main advantages of this technology is improved fuel economy, better drivability, and reduced engine on a emissions by reducing cyclic variations [20] In other researches the Spark plug that achieved the best results was a sparkplug with no ground electrode or surface discharge spark plug as shown in figure 1 where the amount of heat loses were the minimum and there were no barrier influencing the flame growth. COV IMEP was lowest in case of SD spark plug. There was increase in flame speed at the time of beginning and propagation. SD spark plug also offers higher ignition energy helps combustion and extension of flammability limits which helps in the main combustion period [13]. They also posses' quicker burning rates inflate engine performances and engine stability. In this following study we are going to combine this dual spark technology along with SD spark plugs to decrease cyclic variations as much possible to increase engine performances.

2. Methodology

In the initial stage we try to find out the MBT timing of each spark plug configurations i.e. by Conventional Spark plug , Surface ground electrode Spark plug and with dual arrangement of these. We compare performances of each on the basis of maximum brake thermal efficiency. Finally we will compare the worse and best spark plug configurations. In the first stage we find out the performance of this conventional spark plug by changing spark timing .We find out the MBT timing for this configuration as well as measuring performances. In the second stage we have replaced normal J gap spark plug with surface discharge spark plugs. This spark plug that has no grounding electrode and provides three simultaneous sparks per one ignition impulse. We again find out the MBT timing i.e. (Brake Power vs. Spark timing) to measure the performance of spark plug. In the third stage we have first find out correct location for mounting two spark plugs. We have kept positions near to the central location due to space constraints.

After fabrication of cylinder head, two normal J gap spark plugs were mounted on the respective locations. Necessary connections were made for both ignition coils require for both spark plugs connected to CDI unit for simultaneous sparks. Again plot of MBT curve was done & analyze for the performance of dual spark plugs. We want to find out best performance Spark plug configurations in which cyclic variations are minimum. In the fourth stage we have replaced both spark plugs with surface discharge spark plugs. So that fastest flame fronts can be achieved by that along with least combustion durations. Also it generates maximum number of flame fronts which is possible through these configurations. We find out that dual spark plug configuration has best MBT timing. So after comparing cyclic variations of best and worse configuration we are able to achieve our results. Finally we will compare best & worse spark plug configurations on the basis of performance curves. We will compare COV of IMEP at best thermal efficiency to achieve target of this study. We will plot all performance curves for best and worse configurations. In this study we will keep some operating conditions constant like equivalence ratio, MBT timing, engine RPM, throttle percentage etc.

3. Experimental Setup

The engine used for experiments is as mentioned in Table 1. The intake manifold was especially designed for this engine to conduct experiments on electronic carburetion of gaseous phase.

Table 1. Engine specifications

Type	Kirloskar TAF1, air cooled, single cylinder CI engine
Displacement	661 cc
Stroke	110 mm
Bore	87.5 mm
Connecting Rod	234 mm
Compression ratio	17.5:1 (CI version), 10.5:1 (SI version)
Rated Power	4.4 kW @ 1500 rpm
Inlet Valve Open	4.5° bTDC
Inlet Valve Close	35.5° aBDC
Exhaust Valve Open	35.5° bBDC
Exhaust Valve Close	4.5° aTDC

The manifold was provided with throttle valve and a mixing unit for carburetion as shown in figure 2.The intake manifold also had thermocouple and MAP sensor to take intake pressure and temperature measurements. The LPG cylinder was dipped in Hot water bath which maintains a temperature of 50^{o}C and keeps LPG in vapour state. Air Surge tank is used to avoid fluctuating air

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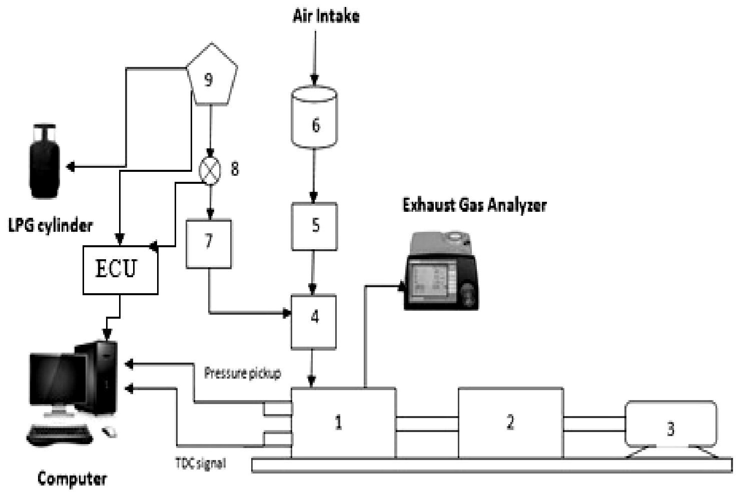
flow during full load condition while a Turbine type flow meter is used to measure air flow rate. Fuel intake system was provided with heating coils which maintain the temperature of the LPG at 50ºC and also helps in maintaining constant supply and reduce pressure fluctuations of fuel during high load conditions. Eddy current Dynamometer by Dynalec controls is used for loading the engine. It keeps the engine speed constant at 1500 rpm while changing the torque. Cranking motor is used for starting the engine as the cranking side of our engine was mounted with crank angle encoder, it can be coupled and decoupled with engine by a magnetic clutch as shown in figure 3. Pressure sensor is mounted on the engine cylinder head which gives Pmax as well as IMEP for consecutive cycles. Inlet air temperature and exhaust gas temperature is measures through temperature sensor displayed on dynamometer controller. Exhaust gas analyses through Horiba analyser and Emersion analyser.



1	Engine
2	Dynamometer
3	Controller
4	Intake manifold
5	Air Flow meter
6	Air drum
7	Fuel Flow meter
8	Throttle Control
9	Gas mixer

Figure 2. Schematic diagram of the Experimental Setup

The ignition set up comprises of CDI unit, ignition coils, high tension cables, Spark plugs. Dual spark plugs are mounted on fabricated cylinder head as shown in figure 5. For igniting fuel air mixture each spark plug is connected to HT cables separately and these are connected to ignition coils as shown in figure 6.These coils are connected to CDI unit. Capacitor discharge unit provide charge every time circuit breaks to primary windings and then by the time this charge converted to very high voltage through secondary windings. It will ignite mixture when it reaches dielectric strength of mixture or ionization occurs.

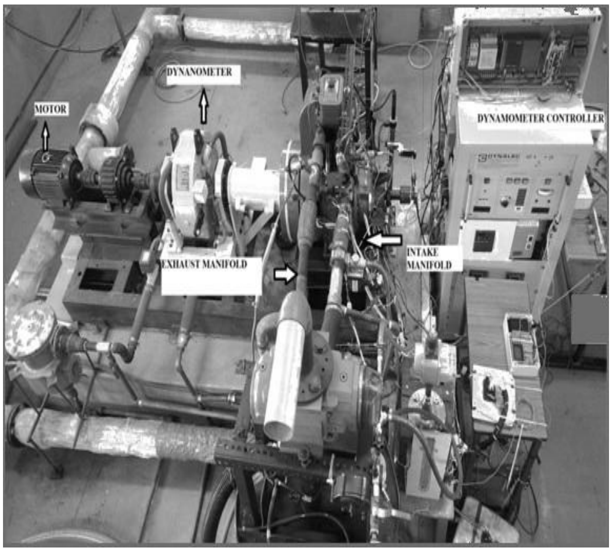


Figure 3. Photographic view of experimental set up

In this experimentation, two types of spark plugs has been used in different configurations. First one is conventional spark plugs or normal J gap spark plug whose is having its ground electrode in the front of central electrode with gap 2-4mm approximately. While other spark plug is no ground electrode spark plug or surface discharges spark plug which has their ground electrode in the form of rings. In this study in order to get pressure values piezoelectric sensor is employed on the cylinder head as well as TDC encoder. P-ϴ curve is obtained with help of DAQ system for requisite number of cycles as required.

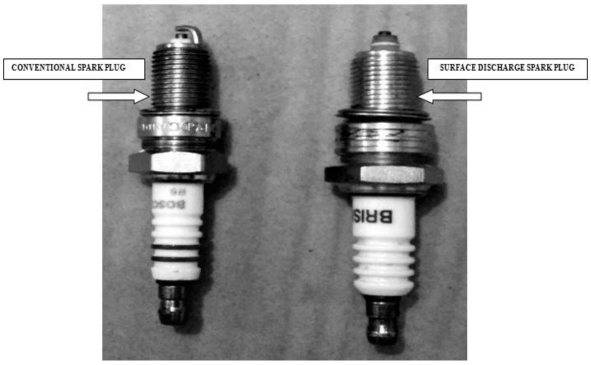


Figure 4. Conventional and surface discharge spark plug

4. Results and Discussions

The performance and emission characteristics of SI engine was obtained by the following configurations,

(i)Single Spark Plug (SSP)
(ii)Surface discharge Single Spark Plug (SD-SSP)
(iii)Dual Spark Plug (DSP)
(iv)Surface discharge Dual Spark Plug (SD-SSP)

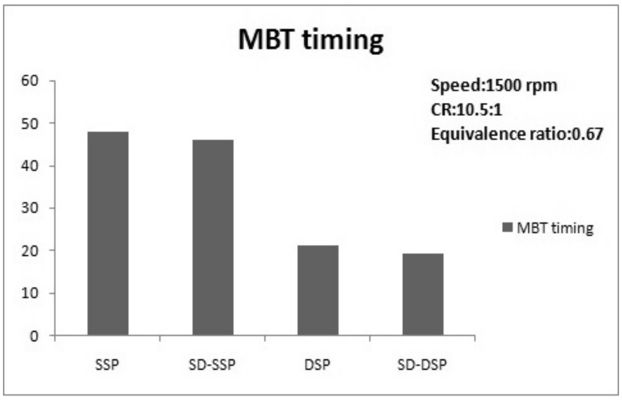


Figure 5. Variation of spark timing against spark plug configuration

In fig.5 MBT Timing for all four spark plug configurations has been shown. It can be clearly noted that dual spark plug cases reduces combustion duration which is a major factor for cyclic variations.

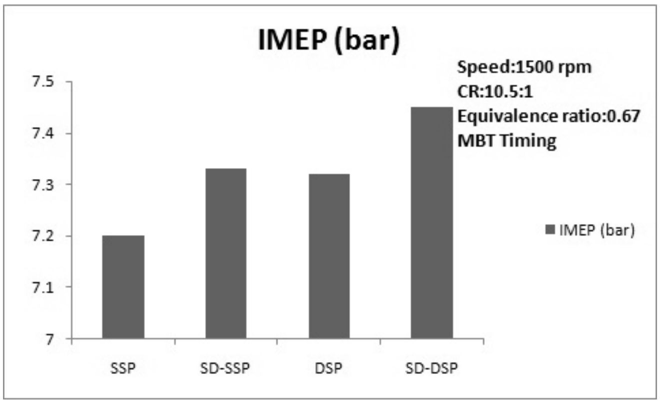


Figure 6. Variation of IMEP against spark plug configurations

As shown in figure 6, Increase in IMEP for all cases of spark plug configurations in comparison to SSP configurations. It is find out 7.45 bar for SD-DSP case which about 3.47% increment to SSP case. So it can refer that multiple spark technology will increase overall IMEP.

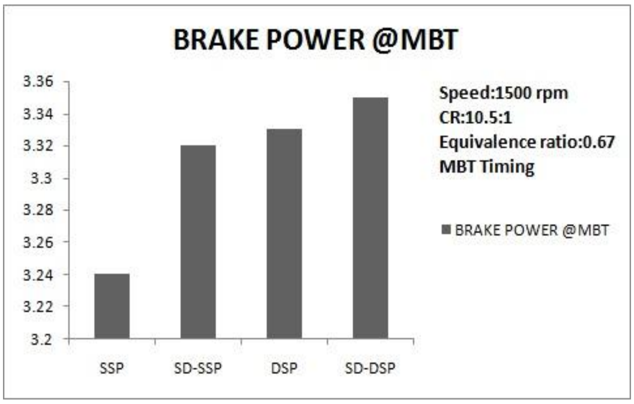


Figure 7. Variation of BP against spark plug configurations

It has shown in figure 7 that SD-DSP configuration gives best Brake Power which is 3.35 kW in comparison to others. Intermediate gives better Brake Power than SSP. Even with SD-SSP configuration has 2.47% increment in Brake Power. Multiple Spark Plug technology providing better combustion than conventional ones.

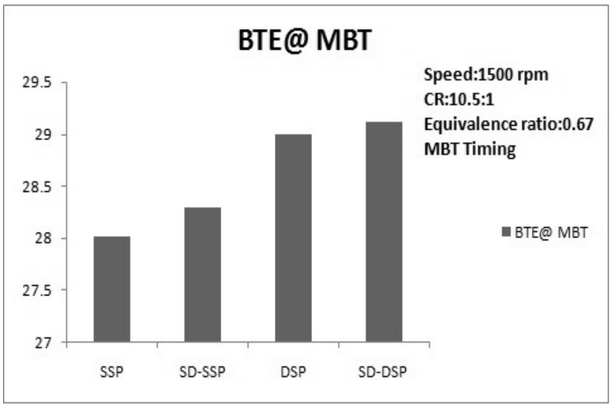


Figure 8. Variation of BTE against spark plug configurations

Brake thermal efficiency is found to be 28% for SSP while it is increases in rest cases. For SD-DSP it is 29.12% which is 3.96 % increment in efficiency as shown in figure 8.

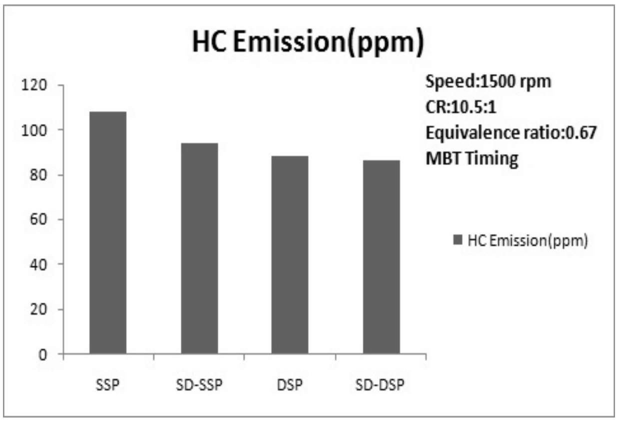


Figure 9. Variation of HC emission against spark plug configurations

Due to multiple flame fronts HC emissions are decreasing. SD-DSP has shown significant improvement in HC emissions reduction .They have reduced HC emissions by 18.5% as shown in figure 9.

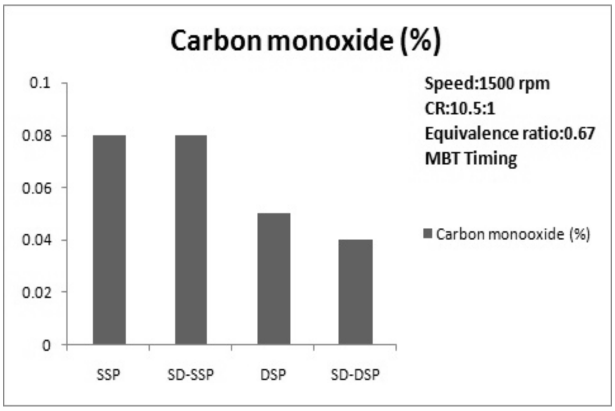


Figure 10. Variation of CO emission against spark plug configurations

It can be observed from the figure 10, there is a reduction in CO emissions for SD-SSP, DSP, SD-DSP configurations as compared to SSP configuration. There is cleaner combustion is felicitated by multiple spark technology along with lean burn operations. Carbon dioxide is increasing from 7.04 % to 8.64% which is significantly large as shown in figure 11 .SSP configuration give best results. The reason behind that are multiple spark plugs providing enough heat to convert CO into CO2 along with lean burn operation.

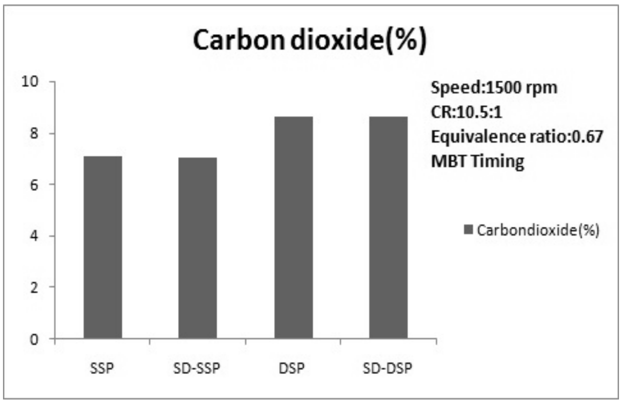


Figure 11. Variation of CO2 emission against spark plug configurations

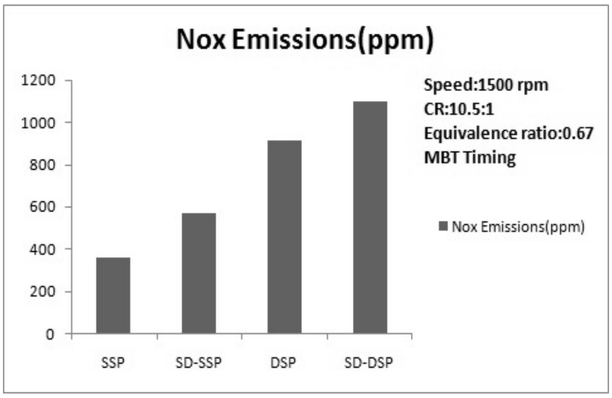


Figure 12. Variation of NOx emission against spark plug configurations

NOx emissions are on higher side with these multiple spark plugs. Conventional plug show least NOx formation around 358 ppm with reduction of 200% as shown in figure 12 .Multiple flame fronts increasing temperature inside cylinder as well as lean burn operation is favorable for NOx formation.

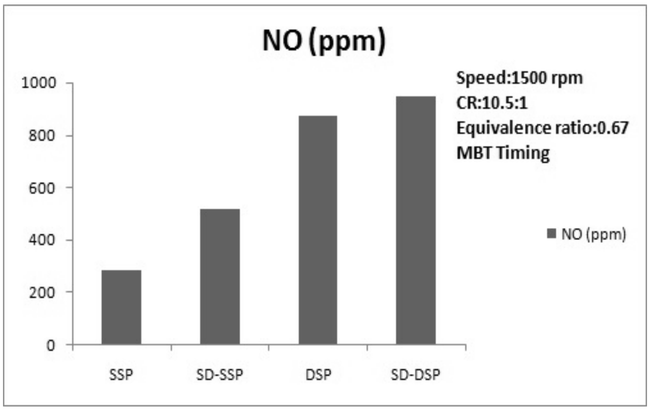


Figure 13. Variation of NO emission against spark plug configurations

Similarly NO emissions is also increasing because of favorable conditions .SSP is showing very low NO emissions i.e. 282 ppm.SD-DSP has shown highest NO emissions as shown in figure 13. While comparing cyclic variations of all configurations @ MBT timing as shown in figure 14.It is measured as 4% in SSP case .It decreases in all other cases like SD-DSP case it is 3.35% which is 16.25% decrement. After finding out best and worse spark plug configurations a brief comparison of SSP and SG-DSP has been done which was better among the four.

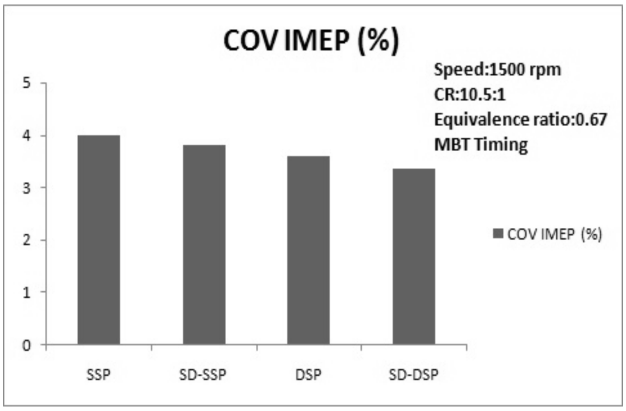


Figure 14. Variation of COV of IMEP against spark plug configurations

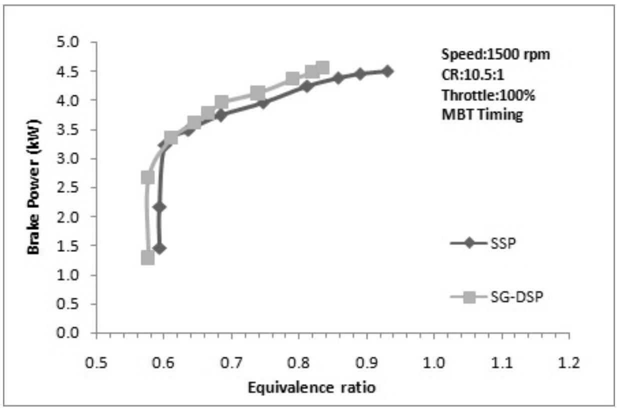


Figure 15. Variation of BP for SSP and SD-DSP

Increase in Brake power can be observed in the graph for SD-DSP configuration as compared to SSP. The maximum power output for SD-DSP was found to be 4.55 kW at equivalence ratio of 0.86 while for SSP it was 4.51 kW at 0.96 as shown in figure 15.This shows SD-DSP configuration can be utilized in lean burning operation as it is giving best performance.

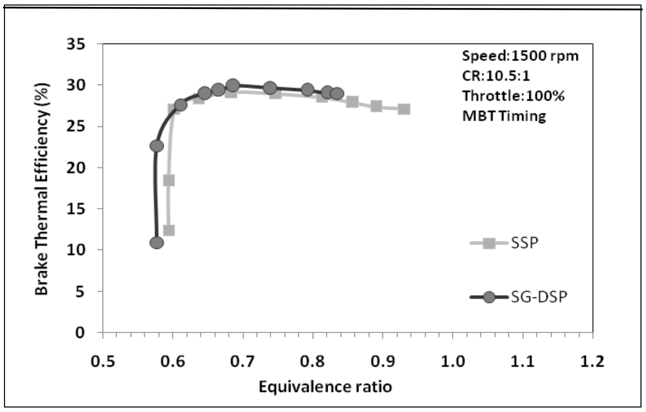


Figure 16. Variation of BTE of SSP and SD-DSP

The maximum BTE for SSP was found to be 28.3 % at equivalence ratio of 0.67 while for SD-DSP it was found to be 29.5 % at equivalence ratio of 0.67 as shown in figure 16. This shows an improvement of 4.24 % in Brake thermal efficiency. The figure 17 shows a significant reduction in HC emissions for SD-DSP mode. The maximum HC for SD-DSP mode is 2100 ppm while for SSP mode it is 4560 ppm.

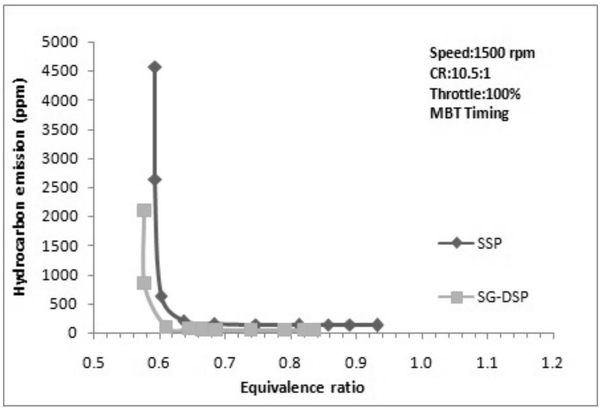


Figure 17. Variation of HC emission of SSP and SD-DSP

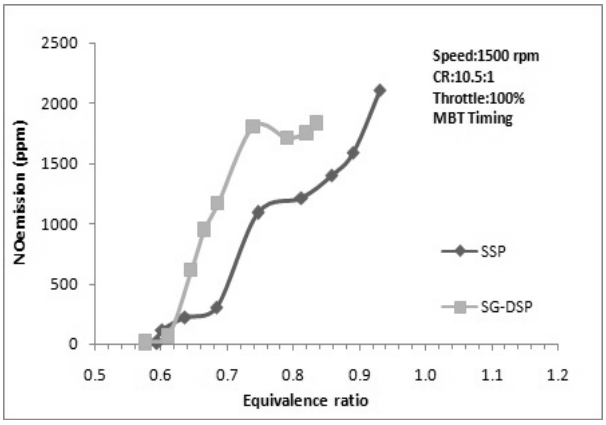


Figure 18. Variation of NO emission of SSP and SD-DSP

NO emissions are increasing significantly SSP mode has shown lowest NO emission i.e. 300 ppm while SD-DSP mode shows highest NO emissions (950ppm) at 0.67 equivalence ratio as shown in figure 18.

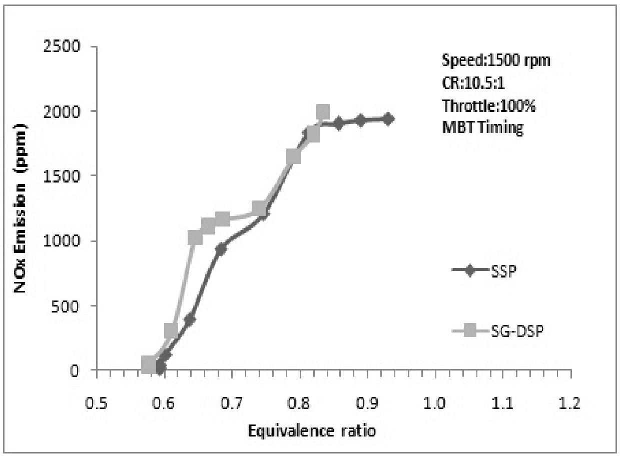


Figure 19. Variation of NOx emissions of SSP and SD-DSP

NOx emissions are very high in both spark plug configurations i.e. around 2000 ppm peak value. As shown in figure 19. They are deteriorating as equivalence ratio is decreasing.

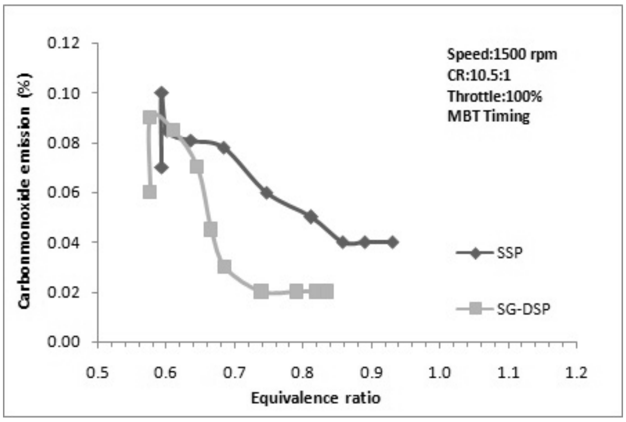


Figure 20. Variation of CO emission of SSP and SD-DSP

It can be observed from the figure 20 there is a reduction in CO emissions for SG-DSP mode as compared to that of SSP mode. At an equivalence ratio 0.67 reduction of 50% in CO emissions. Multiple flame fronts generate enough heat to convert CO into CO_2 in lean burning.

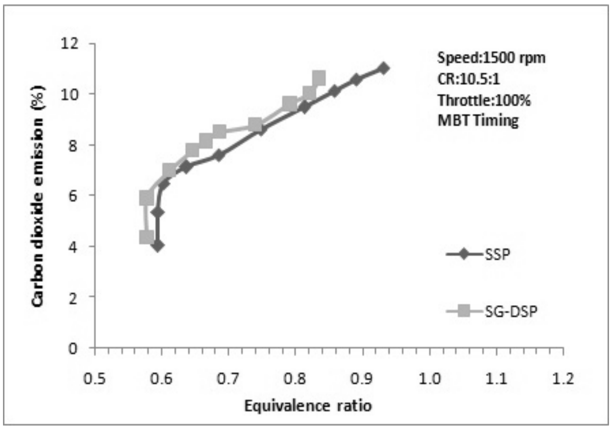


Figure 21. Variation of CO2 emissions of SSP and SD-DSP

Throughout the operation the CO_2 is lesser for SSP mode as compared to the SD-DSP mode as shown in figure 21. Dual spark plug mode produces more heat for the conversion of CO to CO_2. As moving from leaner to richer mixture IMEP is keeping on increasing almost linearly as shown in figure 22. At equivalence ratio 0.67 there is increment of 2.78% which very significant. It improves engine overall power and efficiency.

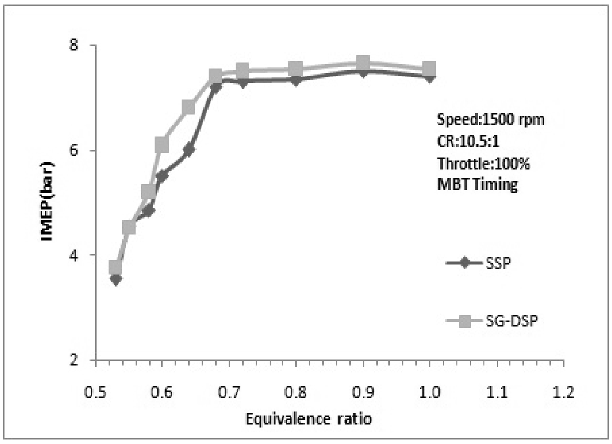


Figure 22. Variation of IMEP of SSP and SD-DSP

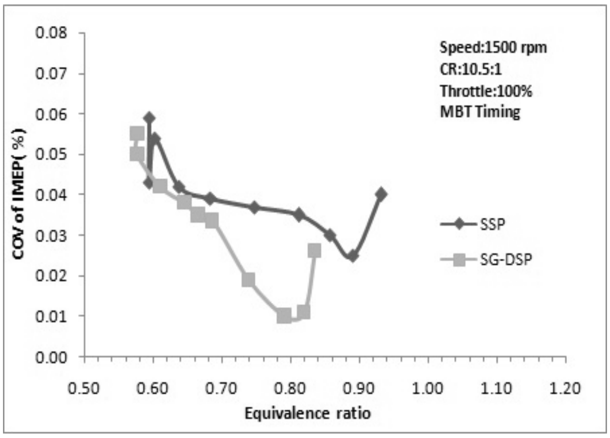


Figure 23. Variation of COV of IMEP of SSP and SD-DSP

Cyclic variations have been reduced in case of SG-DSP mode as it is clearly shown in figure 23. As moving from richer mixture to leaner mixture they are increasing but still MSP technology reduces combustion duration. At 0.67 equivalence ratio 3.35% variations measured in SD-DSP comparison to 4% in SSP mode.

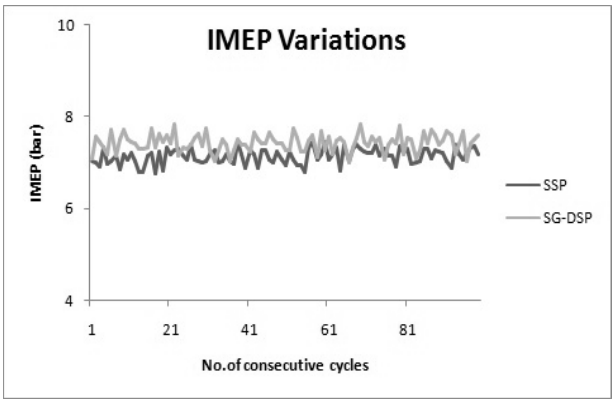


Figure 24. Variation of IMEP of SSP and SD-DSP

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In dual spark plug has low variations as well as high IMEP in comparison to SSP configuration as shown in figure 24.

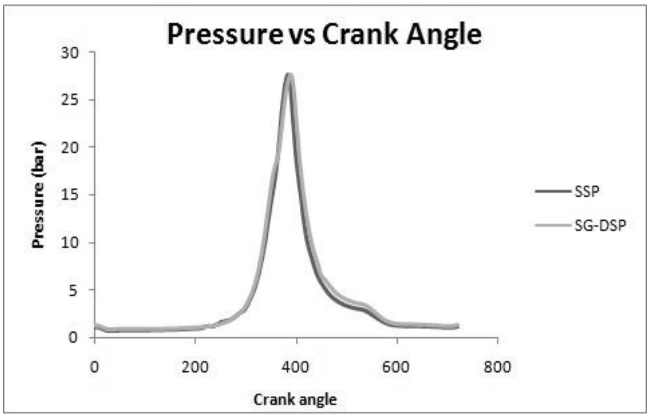

Figure 25. Variation of pressure of SSP and SD-DSP

In the figure 25 clearly shows that average cylinder pressure is more in SD-DSP mode in comparison to SSP mode. This mode not only reduces cyclic variations but also increases average cylinder pressure.

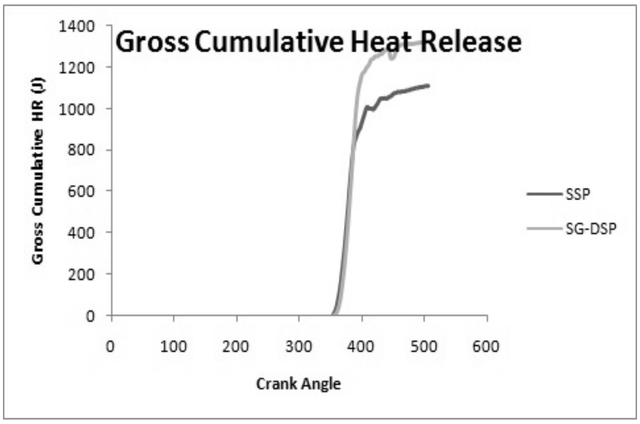

Figure 26. Variation of cumulative HRR of SSP and SD-DSP

Maximum gross cumulative heat release for SD-DSP mode is 1323 J in comparison to SSP mode 1107 J which is increment of 20% at 505 CAD. It clearly showing in figure 26 more heat release due to multiple flame fronts develop during combustion as well as combustion stability.

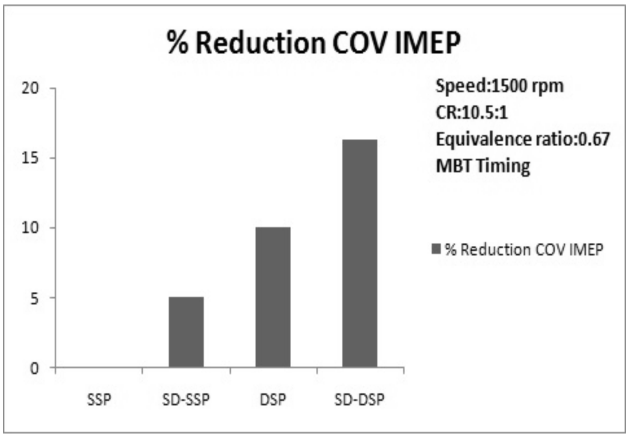

Figure 27. Variation of % reduction of COV of IMEP

Finally COV IMEP has reduced from 4% to 3.35% from SSP to SD-DSP mode which is reduction of 16.25% .Rest other cases reduction of 5% ,10% has been observed in SD-SSP,DSP modes respectively as shown in figure 27.

Table 2. Comparison of Results

Mode	IMEP (bar)	% COV IMEP	% reduction
SSP	7.2	4	0
DSP	7.32	3.6	10
SD-SSP	7.33	3.8	5
SD-DSP	7.45	3.35	16

As shown in Table 2 surface discharge spark plug in dual mode is best configuration. It is showing reduction of 16.25% in COV IMEP. Other configurations are also better in terms of reduction in cyclic variations.

5. Conclusion

The following conclusions are arrived based on the experimental analysis.

- MBT timing for dual spark plug modes is almost half single spark plug modes i.e. 46-48 to 21-18 CAD.
- IMEP for dual spark plug has been increased up to 3.5% in comparison to Single spark plugs.
- Brake power has been increased from 3.24kW to 3.35 kW from SSP to SD-DSP modes respectively which is increment of 2.47%.
- Brake thermal efficiency has been improved from 28 % to 29.12 % in dual spark plug cases with increment of 3.96%.
- HC emission shows 18.5 % reduction in SD-DSP mode.
- CO has been reduced from 8% to 4 % which is very significant from pollution point of view.
- Carbon dioxide shows reduction of 7.04% to 8.64 %.
- NOx and NO emissions become poor for dual spark cases.

Overall surface discharge spark plug in dual spark plug configurations can be very promising way to reduce cyclic variations as well as improving performance of SI engines.

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