EFFECT OF TORROIDAL COMBUSTION CHAMBER SHAPE, NOZZLE GEOMETRY, INJECTION PRESSURE, EGR ON THE PERFORMANCE OF BIODIESEL FUELLED DIESEL ENGINE AND VALIDATION THROUGH TAGUCHI ANALYSIS.

Allamaprabhu.B.Shigihalli[1], Mahantesh M Shivashimpi[2], Akhilesh Patil [3], Aparai Huddar[4]

[1,3,4]UG Students, Dept of Mechanical Engineering, Hirasugar Institute of Technology, Nidasoshi, Karnataka, India.
[2]Professor, Dept of Mechanical Engineering Hirasugar Institute of Technology, Nidasoshi, Karnataka, India.

---***---

Abstract- *An experimental investigation is done on a single cylinder four stroke direct injection diesel engine operated with palm methyl ester (POME) as a biodiesel.*

The performance and emission characteristics were analyzed with torroidal combustion chamber shape, nozzle geometry, injection pressure and EGR.

This study is related to the modification of combustion chamber shape of diesel engine for the proper mixing of air fuel mixture (swirl action).The main objective of the experiment is to study the effect of torroidal combustion chamber shape using biodiesel as a fuel in diesel engine by varying the three parameters (nozzle geometry, injection pressure, EGR) among all these parameters the better operating parameters will be selected using Design Of Experiments (DOE).

Keywords: **Torroidal combustion chamber, Bio diesel(POME), Injection Pressure, Nozzle Geometry, EGR (exhaust gas recirculation), Design of experiments (Taguchi method).**

1. INTRODUCTION

Nowadays all the people on earth are dependent on energy for every aspect of their lives, therefore we must produce more with less, to remain competitive. We must use our resources correctly and help in saving environment. We must develop new methods and technologies for the better efficiency of the diesel engine for the transportation purpose.

Diesel engines are used for transportation and power generation applications due to the high thermal efficiency. However, there is increased importance on improved engine performance, lesser noise and vibration levels and lesser emissions. Due to the increase in energy demand, fossil fuel in the earth crust is decreasing. To overcome these difficulties and meet these demands, we have to use renewable fuels such as biodiesels for diesel engines that has gained greater importance. Renewable energy sources can provide energy to longer periods, and that of fossil fuels don't provide and these have many advantages.[1] Liquid biodiesels properties are closer to diesel hence they are more suitable for diesel engine applications.

Many vegetable oils have been used for biodiesel production and their respective biodiesels are used as alternative fuels in diesel engines. Biodiesels derived from Palm, jatropha, honge , honne, palm, rubber seed, rape seed, mahua, and neem seed oils were used in diesel engine applications.[2-14] Slightly lowered performance with increased emissions and combustion studies was reported for Biodiesels engine operation by several researchers.[2,3,8,9] Effect of various engine parameters such as compression ratio (CR), injection timing (IT), injection pressure and engine loading on the performance and exhaust emissions of a single cylinder diesel engine operated on biodiesel and their blends with diesel were reported in the literature.[15] Retarded injection timings showed significant reduction in diesel NO_x and biodiesel NO_x. Cylinder pressures and temperatures gradually decreased when injection timings were retarded . Others also have performed experiments on CI engine with different vegetable oils at different injection pressures. Better performance, higher peak cylinder pressure and temperature were reported at increased injection pressures.

The combustion chamber of an engine plays a very important role during the combustion process of variety of fossil fuels. In this context, many researchers performed both experimental and simulation studies on the use of various combustion chambers.[16-18] Improvement in air entrainment with increased swirl and injection pressure were reported. The best combustion chamber geometry of the engine showed better performance and emission levels. The Torroidal shaped combustion geometry helps in proper mixing of gaseous fuel with air.

Designed torroidal combustion chamber due to its swirl action helps in the proper mixing of air and fuel mixture due to its its turbulance effect reduced the NO_x emission levels to the maximum extent. The fuel behaviour when it is injected in the combustion chamber its interaction with air is important. It is known that nozzle geometry and cavitations affect evaporation and atomization process of fuels.The changes in the in-cylinder flow results in differing combustion.

Palm oil, as one of the main agricultural products in Malaysia, is mostly applied for biodiesel production in that region.[19] Palm oil-based biofuel could generate a similar efficiency as diesel fuel with lower pollutant emissions, but with higher Sfc. Moreover, palm oil-based biofuel can be applied in compression ignition (diesel) engines without significant modifications. It also can be blended at any percentage level with petroleum diesel to create biodiesel blends. Biodiesel can be produced from palm oil through a transesterification process, [20] in which the triglycerides (free fatty acid and water contents) from palm oil react with an alcohol (ethanol or methanol) to form ethyl or methyl esters (biodiesel) and glycerol. The fleshy inner wall of the palm fruit called mesocarp is processed to obtain the palm oil.

2. EXPERIMENTAL SET- UP

Experiments were conducted on a Kirloskar TV1 type, four stroke, single cylinder, water-cooled diesel engine test. Figure 1(a) and 1(b) shows the schematic experimental set up. Eddy current dynamometer was used for loading the engine. The fuel flow rate was measured on the volumetric basis using a burette and stopwatch. The engine was operated at a rated constant speed of 1500 rev/min. Cooling of the engine was accomplished by circulating water through the jackets of the engine block and cylinder head. The experiments were conducted on the CI engine using POME (palm methyl ester) as injected fuel with Toroidal Combustion chamber for different nozzle geometries (3holes, 4holes and 5holes), injection pressures (220bar, 240 bar, 250 bar) and EGR (5% 10% 15%).

Fig.1 (a) attatched EGR setup

Fig. 1(b) ENGINE set up

Table 1, Engine specifications

Engine	Four stroke, single cylinder
Manufacturer	Kirloskar
BHP	5 HP
RPM	1500
Fuel	Diesel
Bore	80 mm
Stroke length	110 mm
Cooling method	Water cooled
Ignition method	Compression ignition
Compression ratio	1:17.5

2.1 BIODIESEL MANUFACTURING PROCESS

Single stage process (base catalyst process)

1. Measure 1 ltr of oil.
2. Transfer oil into a 3 neck flask provided in lab set.
3. Place the 3 neck flask on magnetic stirrer.
4. Put the magnet pellet into the flask.
5. Fix the condenser to the 3 neck flask and connect to condenser.
6. Connect the magnetic stirrer to electrical connection.
7. Switch on the magnetic stirrer switch.
8. Setup the heating control to 60 deg C and adjust the RPM to get suitable speed for heating oil.
9. Insert the thermometer to the side of 3 neck flask and check temperature.
10. Take 300ml methanol per 1 ltr of oil in a 500 ml beaker.
11. Weigh the required NaOH based on the FFA %.
12. Determined for raw oil and add to methanol stirr well and this mixture is called <u>METHOXIDE</u> mixture.
13. When the temperature reaches 63 deg C, add the methoxide mixture slowly to the hot oil into the 3 neck flask and maintain speed at 200RPM.
14. Maintain the temperature at 60 deg C to 63 deg C (total reaction time is 2 hours) (boiling point of methanol is 64.07 deg C).
15. Run the process for 30min and observe the colour of mixture turns from turbide orange to transparent chilly red.
16. After the 30 min drain a sample and allow it to settle, two distinct layers will be obtained indicating the chemical reaction is proceeding in the equilibrium.
17. From the process for another one and half hour.
18. After one and half hour drain one more sample and observe for 2 separate distinct layer separation.
19. Transfer the mixture into a separating funnel and allow it to settle for 2 hours.

20. After 2 hours, glycerine will settle at the bottom and biodiesel separates as top layer.
21. Drain the glycerine layer from the separating funnel from the bottom carefully and store it.
22. Allow the biodiesel layer to settle for another half an hour and observe if any further glycerine content settles if glycerine layer is seen, then drain the same.
23. Now transfer the biodiesel from reactor to washing cum drying tank DH2 through the pump. Keeping the top lid open after pumping, stop the pump and close the valves.
24. Start washing biodiesel using the bath shower so that hot water particles will come in contact of all the biodiesel particles. Allow the water to settle for 30 min.
25. Drain the water completely.
26. Once again fill up the water tank and rise temperatures to 50 deg C continue washing and draining. Repeat the steps till the water and biodiesel comes to 7pH.
27. Drain the water completely and put on DH2 switch and start drying of biodiesel by open boiling method.
28. When the temperature reaches 105 deg C all the water traces comes out of biodiesel, maintain temperature between 105-110 deg C for 15-20 min.
29. Put of the heater DH2 and allow the biodiesel to cool overnight. Transfer the cooled biodiesel to storage tank.

Table 2, FFA, NaOH chart

FFA of oil	NaOH in gms
0	3.5
1	4.5
2	5.5
3	6.5
4	7.5

Fig.2 sample of oil with 2 distinct layers

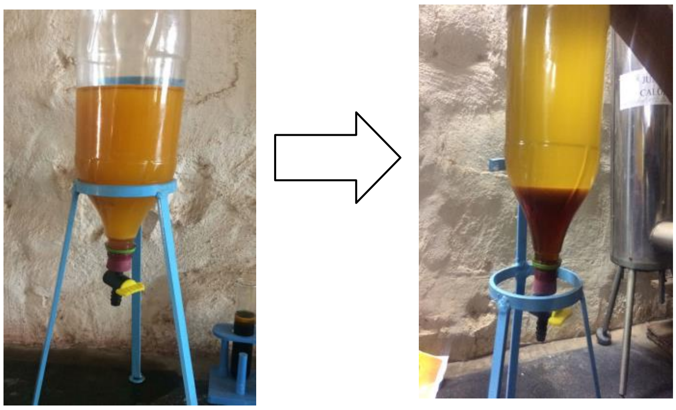


Fig.3 shows the process of settling of glycerin at bottom

Fig.4 heating the biodiesel at 110 to 115 C to remove water and methanol content

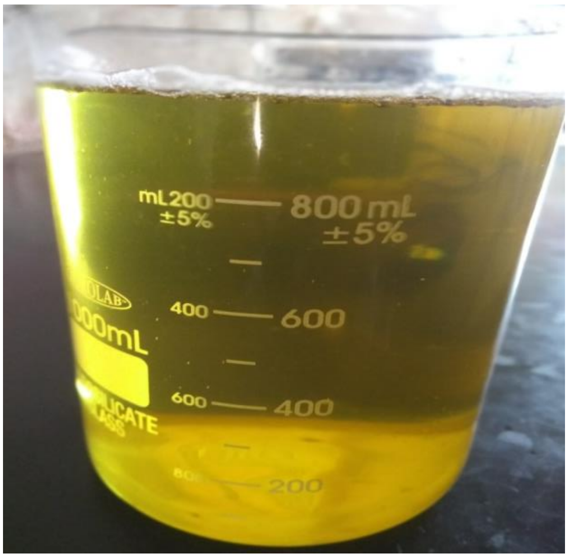


Fig.5 After heating finally the POME biodiesel is ready for use.

Table 2 Properties of POME in comparison with Diesel

Sl.No.	Properties	Diesel	POME
1	Density (kg/m³)	840	880
2	Energy density (kJ/kg)	42,000	38,400
3	Viscosity at 40° C(cSt)	2-5	3.94
4	Flash Point (°C)	75	160
5	Cetane Number	45-55	---
6	Carbon Residue (%)	0.1	---
7	Pour point (°C)	-5	---

3. EXPERIMENTAL WORK

1. First start the engine by cranking and allow it to attend steady speed for 2-5 min then measure the speed of engine and corresponding temperature and manometer reading and time taken to consume 10cc of fuel.
2. Add 4 kg weight and allow it to attain steady speed and note down corresponding readings.
3. And repeat the same procedure for 8 kg, 12 kg, 16kg load and note down the reading.
4. Above procedure are carried out for 3, 4, 5 hole nozzle and 220 bar, 240 bar, 250 bar pressure with EGR 5%, 10%, 15%.
5. Then replace the hemispherical shape piston by torroidal shape piston and note down the corresponding reading for 4 kg, 8 kg, 12 kg, 16 kg and for 3, 4, 5 nozzle hole with injection pressure of 220 bar, 240 bar, 250 bar and EGR 5%, 10%, 15%.
6. The tests are carried out using Palm biodiesel and Diesel as a fuel.
7. Finally the comparison are made between diesel fuel and palm biodiesel.
8. The L9 array formed to conduct the experiment and optimize the parameters of engine using taguchi method shown in below table.

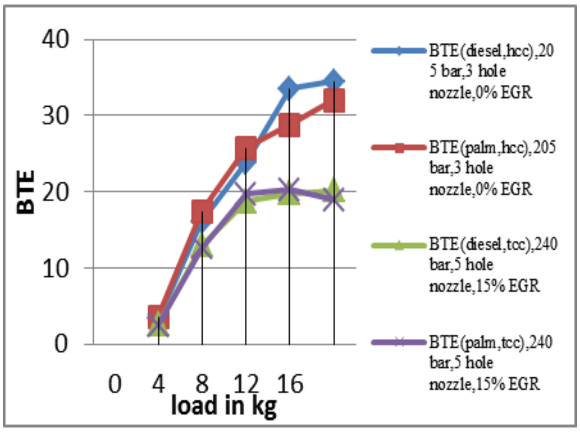
Table 3, L9 array

↓	C1	C2	C3
	IP	N	EGR
1	220	3	5
2	220	4	10
3	220	5	15
4	240	3	10
5	240	4	15
6	240	5	5
7	250	3	15
8	250	4	5
9	250	5	10

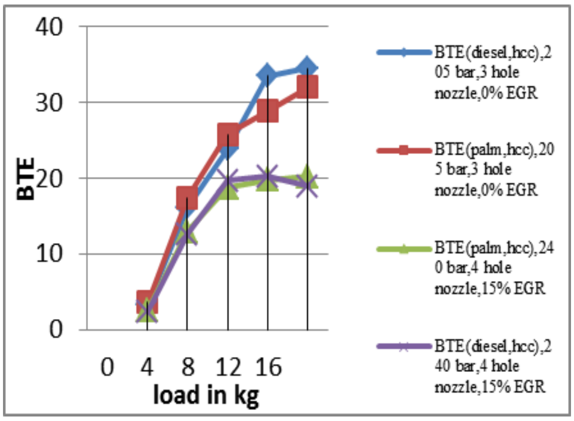
4. RESULTS AND CONCLUSION

4.1 Effect of BTE with LOAD in kg.

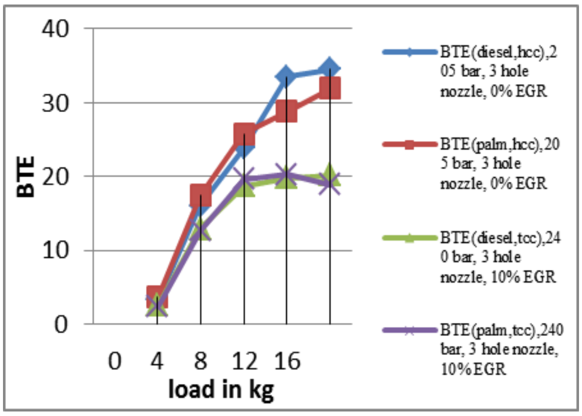
4.1.1 IOP= 240 bar NG = 5 hole EGR=5%



4.1.2 IOP= 240 bar NG = 4 hole EGR=15%

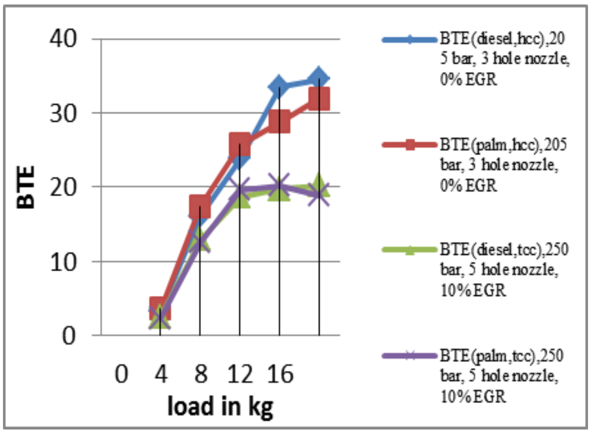


4.1.3 IOP= 240 bar NG = 3 hole EGR=10%

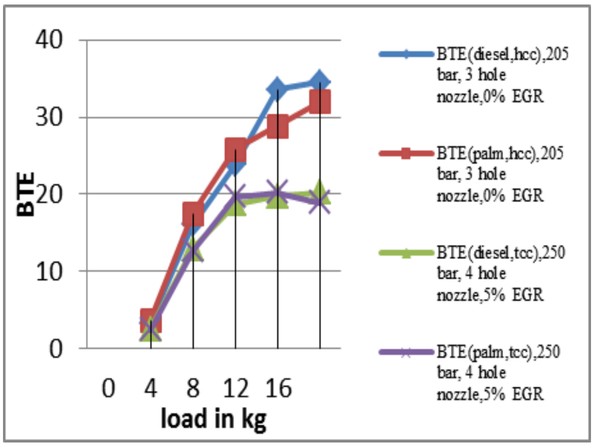


Form the above graph, 4.1.1, 4.1.2, 4.1.3, HCC shape with 3 holes nozzle geometry operated with diesel and POME showing higher BTE than remaining combination due to lower viscosity. Among 3 hole nozzle, 10% EGR and 240 bars shows maximum BTE than other combinations of POME operated diesel engine with TCC shape. This is due to higher injection pressure leads to better atomization characteristics.

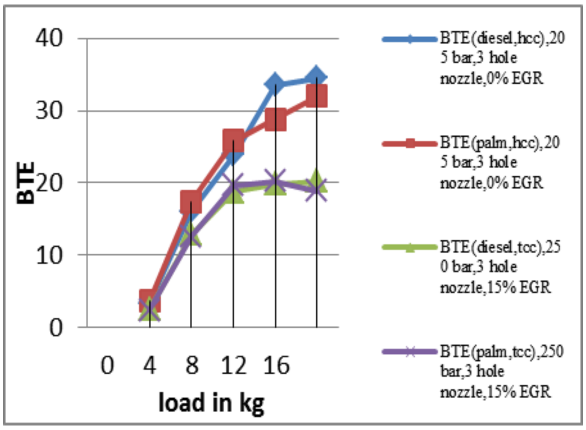
4.1.4 IOP= 250 bar NG = 5 hole EGR=10%



4.1.5 IOP= 250 bar NG= 3 hole EGR=15%

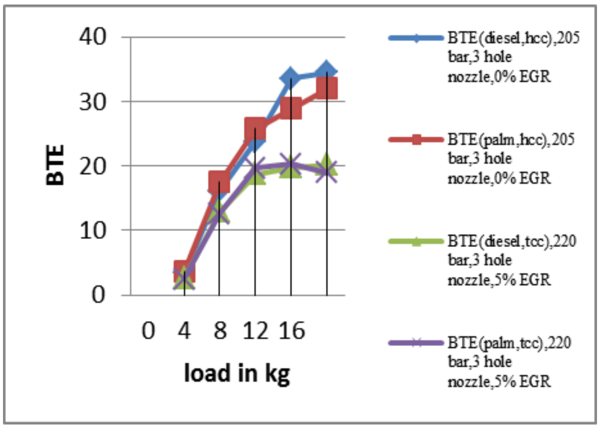


4.1.6 IOP= 250 bar NG= 3 hole EGR=5%

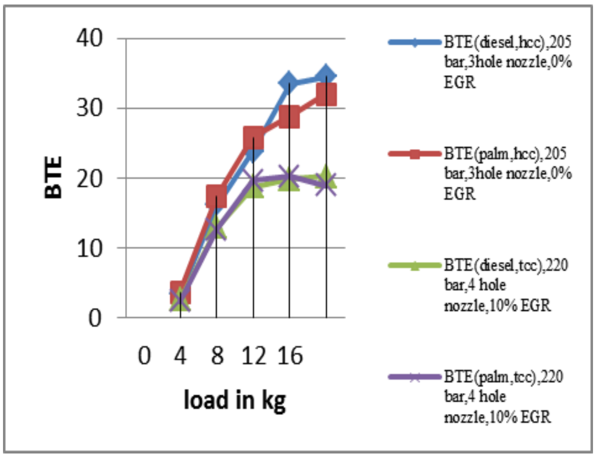


From the above graph, 4.1.4, 4.1.5, 4.1.6, HCC shape with 3 holes nozzle geometry operated with diesel and POME showing higher BTE than remaining combination due to lower viscosity. Among 3 hole nozzle, 15% EGR and 250 bars shows maximum BTE than other combinations of POME operated diesel engine with TCC shape. This is due to high valve impinging characteristics leads to more fuel consumption.

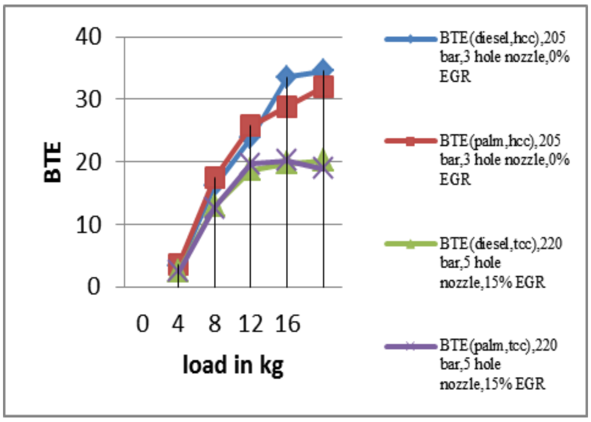
4.1.7 IOP= 220 bar NG= 3 hole EGR=5%



4.1.8 IOP= 220 bar NG= 4 hole EGR=10%



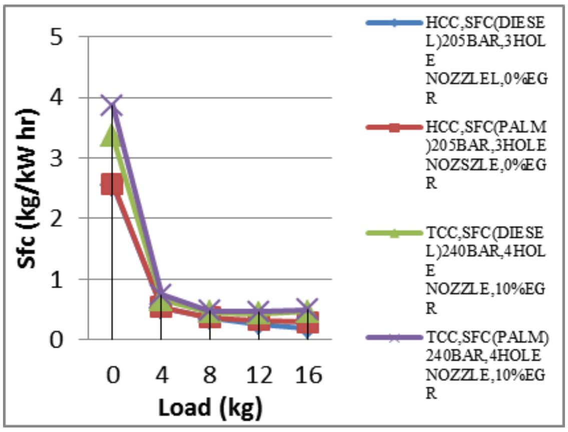
4.1.9 IOP= 220 bar NG= 5 hole EGR=15%



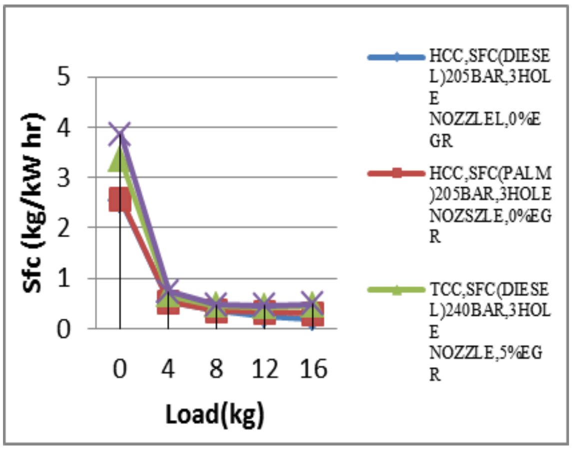
Form the above graph, 4.1.7, 4.1.8, 4.1.9, HCC shape with 3 holes nozzle geometry operated with diesel and POME showing higher BTE than remaining combination due to lower viscosity. Among 3 hole nozzle, 5% EGR and 220 bars shows maximum BTE than other combinations of POME operated diesel engine with TCC shape. This is due to lower injection pressure leads to better atomization characteristics.

4.2 Effect of Specific fuel Consumption in kg/kW-hr with Load in kg.

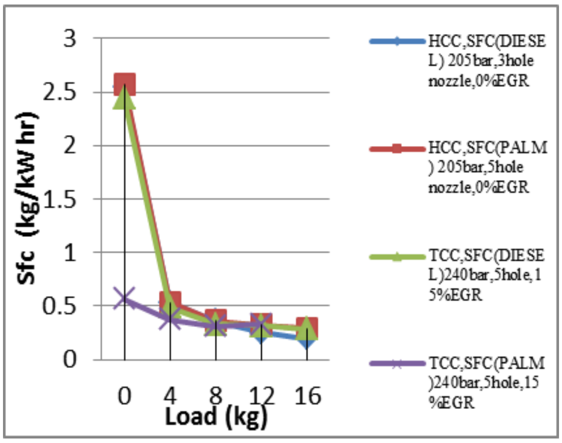
4.2.2 IOP= 240 bar NG= 4 hole EGR=15%



4.2.3 IOP= 240 bar NG= 3 hole EGR=10%

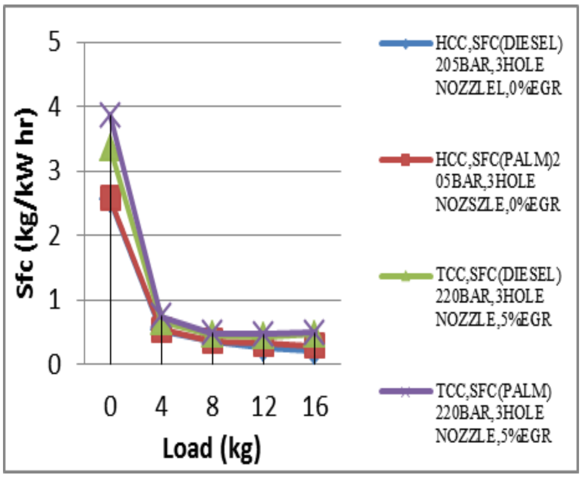


4.2.1 IOP= 240 bar NG= 5 hole EGR=5%

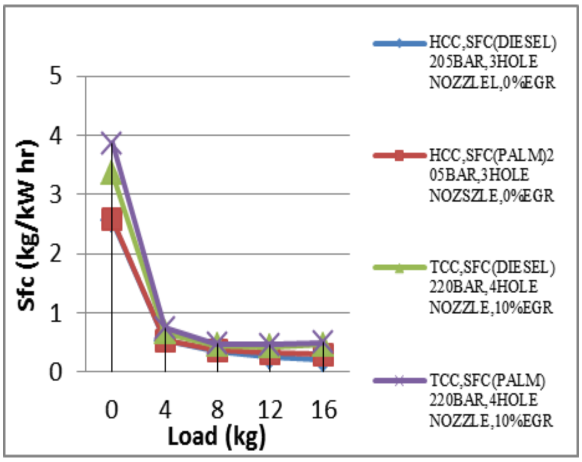


From the above graph, 4.2.1, 4.2.2, 4.2.3, HCC shape with 3 holes nozzle geometry operated with diesel and POME showing lesser SFC than remaining combination due to lower viscosity. Among these combinations 240 bar pressure, 3 hole nozzle and 10% EGR shows less SFC due to proper conversion of chemical energy content of the fuel into useful work.

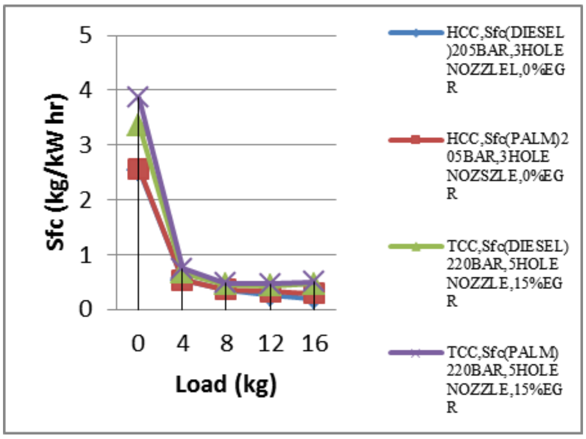
4.2.4 IOP= 220 bar NG= 3 hole EGR=5%



4.2.5 IOP= 220 bar NG= 4 hole EGR=10%

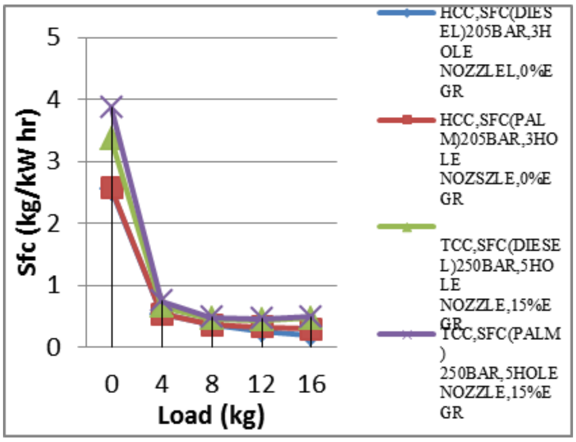


4.2.6 IOP= 220 bar NG= 5 hole EGR=15%

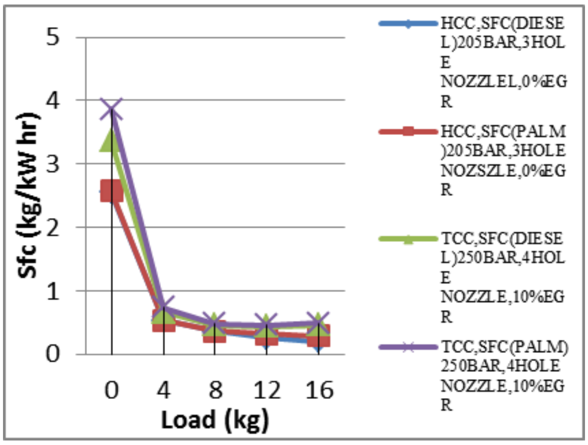


From the above graph, 4.2.4, 4.2.5, 4.2.6, HCC shape with 3 holes nozzle geometry operated with diesel and POME showing lesser SFC than remaining combination due to lower viscosity. Among these combinations 220 bar pressure, 3 hole nozzle and 5% EGR shows less SFC due to proper conversion of chemical energy content of the fuel into useful work.

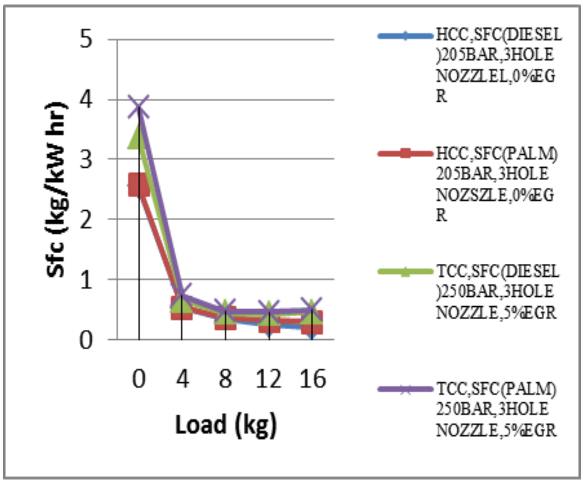
4.2.7 IOP= 250 bar NG= 5 hole EGR=10%



4.2.8 IOP= 250 bar NG= 3 hole EGR=15%



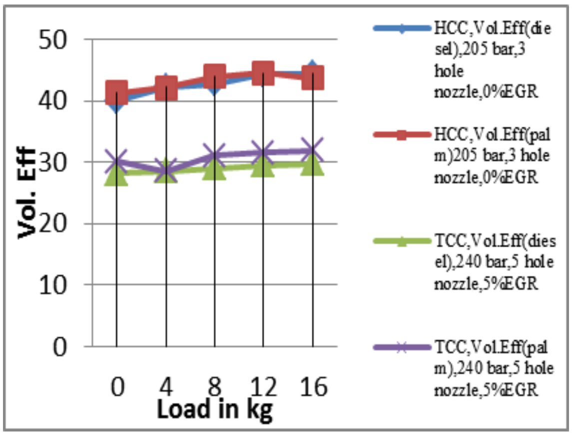
4.2.9 IOP= 250 bar NG= 3 hole EGR=5%



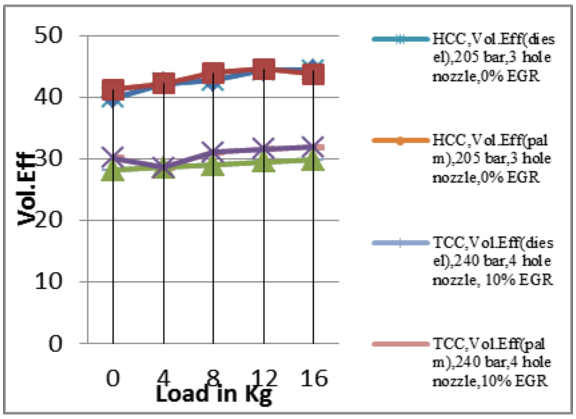
From the above graph, 4.2.7, 4.2.8, 4.2.9, HCC shape with 3 holes nozzle geometry operated with diesel and POME showing lesser SFC than remaining combination due to lower viscosity. Among these combinations 250 bar pressure, 3 hole nozzle and 15% EGR shows less SFC due to proper conversion of chemical energy content of the fuel into useful work.

4.3 Effect of Volumetric Efficiency with Load in kg.

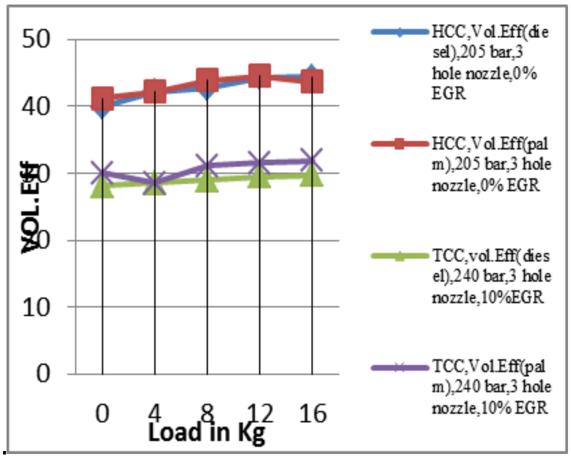
4.3.1 IOP= 240 bar NG= 5 hole EGR=5%



4.3.2 IOP= 240 bar NG= 4 hole EGR=15%.

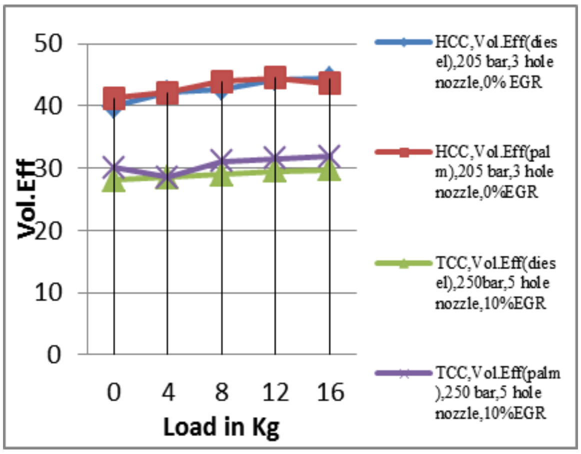


4.3.3 IOP= 240 bar NG= 3 hole EGR=10%

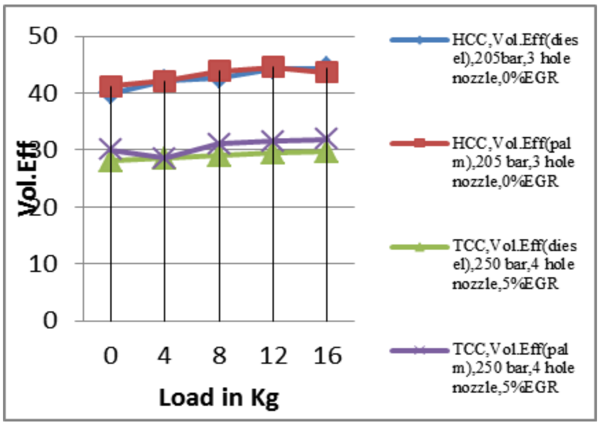


From the above graph,4.3.1, 4.3.2, 4.3.3, HCC shape with 3 holes nozzle geometry operated with diesel and POME showing lesser Volumetric efficiency than remaining combination due to lower viscosity. Among these combinations 240 bar pressure, 3 hole nozzle and 10% EGR shows slightly lower Volumetric efficiency compared to 250 bar pressure.

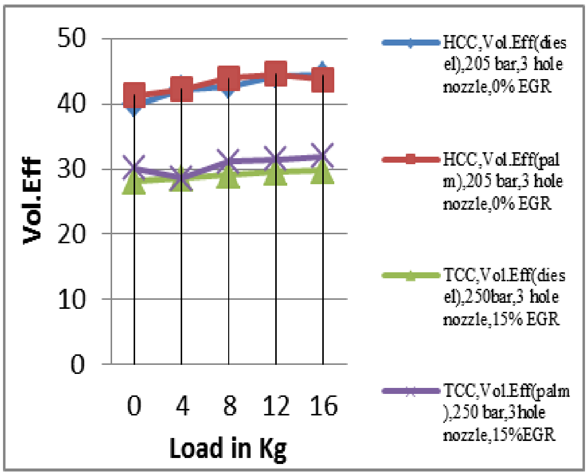
4.3.4 IOP= 250 bar NG= 5 hole EGR=10%



4.3.5 IOP= 250 bar NG= 4 hole EGR=5%

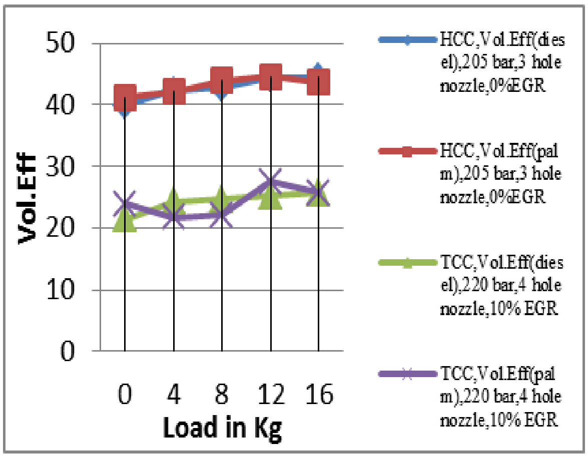


4.3.6 IOP= 250 bar NG=3hole EGR=10%

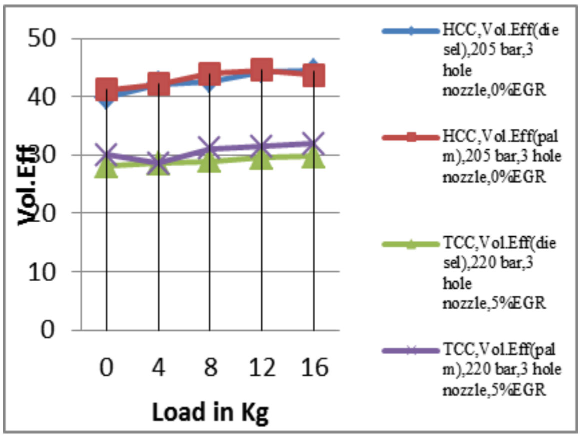


From the above graph,4.3.4, 4.3.5, 4.3.6, HCC shape with 3 holes nozzle geometry operated with diesel and POME showing lesser Volumetric efficiency than remaining combination due to lower viscosity. Among these combinations 250 bar pressure, 3 hole nozzle and 15% EGR shows higher volumetric efficiency due to high intake pressure.

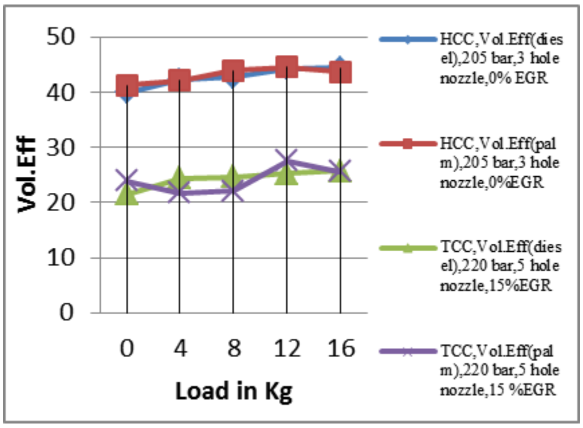
4.3.7 IOP= 220 bar NG= 4 hole EGR=10%



4.3.8 IOP= 220 bar NG= 3 hole EGR=5%



4.3.9 IOP= 220 bar NG= 5 hole EGR=15%



From the above graph,4.3.7, 4.3.8, 4.3.9, HCC shape with 3 holes nozzle geometry operated with diesel and POME showing lesser Volumetric efficiency than remaining combination due to lower viscosity. Among these combinations 220 bar pressure, 3 hole nozzle and 5% EGR shows slightly lower Volumetric efficiency compared to 250 bar pressure.

5. DESIGN OF EXPERIMENTS

5.1 TAGUCHI METHOD

It is a statistical method or robust design method developed by GENICHI TAGUCHI to improve the quality of manufactured goods & more recently applies to engineering, biotechnology, marketing & advertising.

5.2 Steps involved for analysis of experiments are as follows:

1. To create Taguchi design first we have to consider 3-level design (2-13 factors) and next we have to select number of factors required to carry out the analysis.
2. Choose L9 array(2-4 levels)(3×3matrix)
3. Enter the name of factors with the number of inputs (based on the level selected. For Ex=for 3 level 3 inputs)
4. Then finally we will get L9 array according to that we are conducting experiments.

L9 ARRAY

Table 5.1, L9 array of diesel fuel

↓	C1	C2	C3
	IP	N	EGR
1	220	3	5
2	220	4	10
3	220	5	15
4	240	3	10
5	240	4	15
6	240	5	5
7	250	3	15
8	250	4	5
9	250	5	10

5. Then enter the result of the set of experiments conducted in column C4.

Table 5.2, L9 array of diesel fuel

↓	C1	C2	C3	C4
	IP	N	EGR	BTE
1	220	3	5	26.190
2	220	4	10	18.511
3	220	5	15	20.210
4	240	3	10	30.103
5	240	4	15	18.380
6	240	5	5	20.800
7	250	3	15	25.530
8	250	4	5	20.550
9	250	5	10	20.710

6. Then next step is to analyze the taguchi by entering response data.

7. Select the signal to noise ratio graph for analysis.

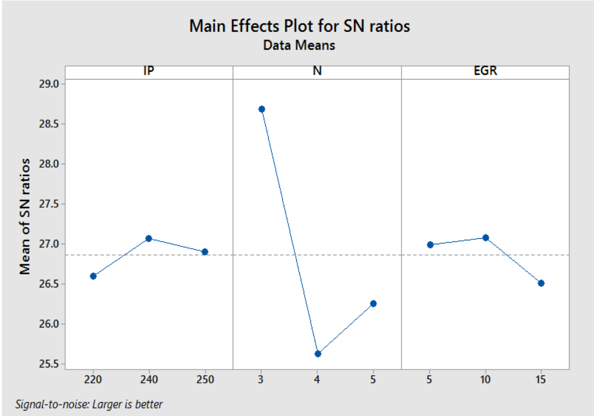


Fig.6 Graph of SN ratio's (NOTE- larger is better)

8. Fit the general linear model by selecting responses and factors.

9. Fit the regression model to create the regression equation, which is used to calculate the theoretical brake thermal efficiency.

REGRESSION EQUATION

BTE=30.2+0.0283 IP -3.35 N-0.114 EGR

10. Then comparison is made between theoretical value and experimental value.

5.3 VALIDATION THROUGH TAGUCHI

(L9 ARRAY) FOR DIESEL FUEL

Injection pressure	Nozzle Geometry	EGR	BTE	SN ratio
220	3	5	26.19	28.36
220	4	10	18.51	25.34
220	5	15	20.21	26.11
240	3	10	30.10	29.57
240	4	15	18.38	25.28
240	5	5	20.80	26.36
250	3	15	25.53	28.14
250	4	5	20.55	26.25
250	5	10	20.71	26.32

5.4 ANALYSIS OF VARIENCE

Source	DF	Adj SS	Adj MS	f-Value	P-value	%
IP	2	3.207	1.603	0.43	0.701	2.497%
Nozzle	2	112.99	56.496	15.04	0.062	88.01%
EGR	2	4.662	2.331	0.62	0.617	3.631%
Error	2	7.514	3.757			5.85%
TOTAL	8	128.374				**99.98%**

5.5 RESPONSE TABLE FOR SIGNAL TO NAOISE RATIO

LEVEL	IP	NOZZLE	EGR
1	26.61	28.69	26.99
2	27.07	25.63	27.08
3	26.91	26.27	26.51
DELTA	0.47	3.06	0.57
RANK	3	1	2

According to the set of experiments,

- Primary cause for increase in brake thermal efficiency is NOZZLE.
- Secondary cause for increase in brake thermal efficiency is EGR.
- Tertiary cause for increase in brake thermal efficiency is INJECTION PRESSURE

5.6 REGRESSION EQUATION

BTE=30.2+0.0283 IP -3.35 N-0.114 EGR

Injection pressure	Nozzle Geometry	EGR	BTE (Expt)	BTE (Theo)
220	3	5	26.19	25.356
220	4	10	18.51	21.886
220	5	15	20.21	17.216
240	3	10	30.10	25.80
240	4	15	18.38	21.882
240	5	5	20.80	19.672
250	3	15	25.53	25.515
250	4	5	20.55	23.305
250	5	10	20.71	19.38

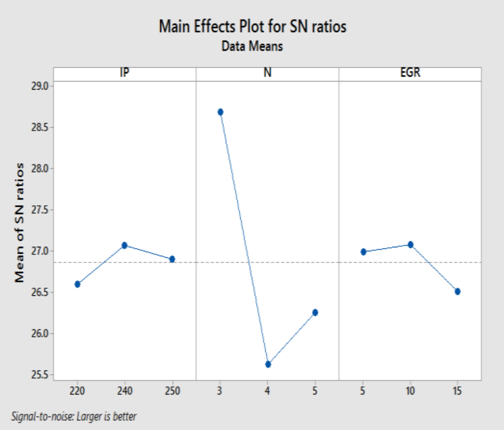


Fig.7 Graph of SN ratio for Diesel fuel (larger is better)

- According to the graphs, the nominal operating parameters are 240 bar pressure, 3hole nozzle and 10% EGR

5.7 FOR PALM METHYL ESTER

L9 ARRAY

Injection pressure	Nozzle Geometry	EGR	BTE	SN ratio
220	3	5	26.19	27.92
220	4	10	18.51	25.52
220	5	15	20.21	25.53
240	3	10	30.10	29.04
240	4	15	18.38	24.39
240	5	5	20.80	26.99
250	3	15	25.53	26.03
250	4	5	20.55	25.46
250	5	10	20.71	26.50

5.8 ANALYSIS OF VARIENCE

Source	DF	Adj SS	Adj MS	f-Value	P-value	%
IP	2	9..159	4.580	2.35	0.298	8.73%
Nozzle	2	60.735	30.368	15.61	0.060	57.94%
EGR	2	31.021	15.511	7.97	0.111	29.59%
Error	2	3.890	1.945			3.711%
TOTAL	8	104.806				**99.97%**

5.9 RESPONSE TABLE FOR SIGNAL TO NAOISE RATIO

LEVEL	IP	NOZZLE	EGR
1	26.33	27.67	26.79
2	26.81	25.13	27.02
3	26.00	26.35	25.32
DELTA	0.81	2.54	1.70
RANK	3	1	2

According to the set of experiments,

- Primary cause for increase in brake thermal efficiency is NOZZLE.
- Secondary cause for increase in brake thermal efficiency is EGR.
- Tertiary cause for increase in brake thermal efficiency is INJECTION PRESSURE.

5.10 REGRESSION EQUATION

BTE = 35.5 - 0.0155 IP - 1.80 N - 0.349 EGR

Injection pressure	Nozzle Geometry	EGR	BTE (Expt)	BTE (Theo)
220	3	5	24.90	24.94
220	4	10	18.89	21.40
220	5	15	18..92	17.85
240	3	10	28.32	22.89
240	4	15	16.59	19.34
240	5	5	22.37	21.03
250	3	15	20.04	20.99
250	4	5	18.75	22.68
250	5	10	21.15	19.13

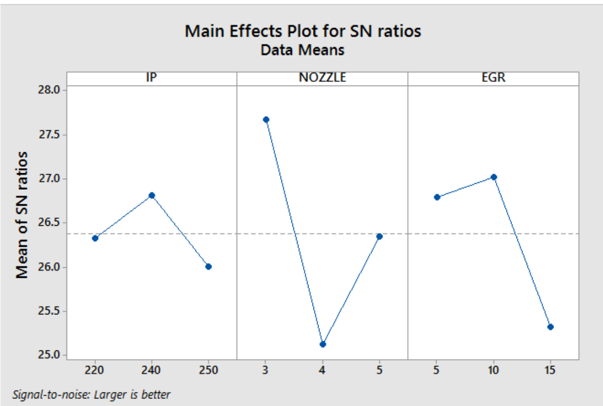


Fig.8 Graph of SN ratio for Palm methyl ester

- According to the graphs, the nominal operating parameters are 240 bar pressure, 3hole nozzle and 10% EGR

6. CONCLUSIONS

- BTE is higher for diesel in TCC without EGR compared to with EGR and POME gives higher BTE at 240 bar, 3 hole nozzle and 10% EGR.
- Volumetric efficiency is higher for HCC without EGR compared to with EGR due to high inlet temperature and diluting the mixture.
- The Specific fuel consumption has reduced with increase in load. The HCC shape with diesel fuel is reduced more compared to TCC shape with POME fuel.
- Engine parameters are optimized for diesel and POME fuels by using taguchi method for POME & diesel fuels at 240 bar injection pressure, 3 hole nozzle geometry and 10% EGR for TCC shape in diesel engine.
- By overall. By using POME fuel in existed diesel engine with suitable modification, the engine performance can be enhanced as near to mineral diesel fuel efficiency. Hence POME fuel can be used as an alternative fuel in diesel engine to save huge amount of the fossil fuel requirement in our country and worldwide.

7. REFERENCES

1] Goldemberg J, Coelhobn ST (2004) Renewable energy-traditional biomass vs. modern biomass. Energy Policy 32: 711-714.

2] Banapurmath NR, Tewari PG (2008) Combustion and emission characteristics of a Direct Injection CI engine when operated on Honge oil and diesel. International Journal of Sustainable Engineering 1: 80-93.

3] McCracken ME, Abraham J (2001) swirl spray interaction in a diesel engine . society of automotive engineers.2001-01-0996

4] Bari S, Lim TH, Yu CW (2002) Effect of Preheating of Crude Palm Oil (CPO) on injection system performance and emision of a diesel engine.Renewable Energy 27:339-351.

5] Sundraapandian S, Devaradjane G (2007) Experimental and Theoretical investigation of the performance of vegetable-oil-operated CI engine. Society of Automotive Engineers, Paper No: 2007-32-0067.

6] Karnwal A, Naveen Kumar MM, Chaudhary HR, Siddiquee AN, Khan ZA (2010) Production of Biodiesel from Thumba Oil: Optimization of Process Parameters, Iranica. Journal of Energy & Environment 1: 352-358.

7] Gajendra Babu MK, Chandan Kumar, Das LM (2006) Experimental investigations on a Karanja Oil Methyl Ester

Fuelled DI Diesel Engine. Society of Automotive Engineers, Paper No: 2006-01-0238, USA.

8] Ramadhas AS, Jayaraj S, Muraleedharan C (2005) Characterization and effect of using rubber seed oil as fuel in the compression ignition engines. Renewable Energy 30: 795-803.

9] Raheman H, Phadatare AG (2004) Diesel engine emissions and performance from blends of karanja methyl ester and diesel. Biomass and Bioenergy 27: 393-397.

10] Ramadhas AS, Muraleedharan C, Jayaraj S (2005) Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. Renewable Energy 30: 1789-1800.

11] Sahoo PK, Das LM, Babu MKJ, Naik SN (2007) Biodiesel development from high acid value polanga seed oil and performance evaluation in a CI engine. Fuel 86: 448-454.

12] Onga HC, Mahlia TMI, Masjukia HH, Norhasyimab RS (2011) Comparison of palm oil, Jatropha curcas and Calophyllum inophyllum for Biodiesel. Renewable and Sustainable Energy Reviews 15: 3501-3515.

13] Sahoo PK, Das LM, Babu MKJ, Arora P, Singh VP, et al. (2009) Comparative evaluation of performance and emission characteristics of Jatropha, karanja and polanga based biodiesel as fuel in a tractor engine. Fuel 88: 1698-1707.

14] Venkanna BK, Reddy CV (2011) Performance, emission and combustion characteristics of direct injection diesel engine running on *calophyllum*

15] Gajendra Babu MK (2007) Studies on performance and exhaust emissions of a CI engine operating on diesel and diesel biodiesel blends at different injection pressures and injection timings. Society of Automotive Engineers, Paper No.: 2007-01-0613, USA.

16] Risi AD, Donateo T, Laforga D (2003) Optimisation of combustion chamber of direct injection diesel engines. SAE International Paper No. 2003-01-1064.

17] Jaichander S, Annamalai K (2012) Performance and exhaust emission analysis on pongamia biodiesel with different open combustion chambers in a DI diesel engine. Journal of scientific and industrial research 71: 487-491.

18] Matsumoto K, Inoue T, Nakanishi K, Okumura T (1977) The effects of combustion chamber design and compression ratio on emissions, fuel economy and octain number requirement. Society of Automotive Engineers.

19] Balu Nambiappan (2018) the future of palm oil as a major global crop. Journal of Oil Palm Research Vol. 30 March 2018 (p. 13-25)

20] Eman N Ali , 2013 Characterisation of Biodiesel produced from palm oil via base catalyzed Transesterification. Procedia engineering, volume 53, 2013 pages 7-12.