Dissertation report
on

"Combustion and performance analysis of VCR diesel engine enriched with hydrogen"

Submitted By:
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(2013PME5119)

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Contents

Objective of the Work

- To carry out the combustion and performance analysis of VCR engine fuelled with hydrogen enriched diesel at varying compression ratios and varying loads, at a fixed injection timing and injection pressure, and to compare the effects with that of neat diesel.

Literature review

Experimental works on hydrogen enriched CI engine

Article	Authors	Experiment /Research	Findings/Conclusion
"Hydrogen combustion in a compression ignition diesel engine "(2009) Int. Journal of Hyd. Energy [1]	Szwaja Stanislaw, Grab-Rogalinski Karol	The experiments were performed at a compression ratio of 17:1 in the range from 0% to 17% of hydrogen percentage.	Hydrogen (about 5%) shorten the diesel ignition lag, decrease the rate of pressure rise, increases engine durability.
"Performance and emission studies of direct injection C.I. engine in duel fuel mode (hydrogen-diesel) with EGR "(2012) [2]	Yadav Vinod Singh, Soni S.L., Sharma Dilip	Kirloskar constant rpm (1500), at 16.5:1 C.R., at constant hydrogen flow rate of 40 gm/hr with no EGR, 10% EGR and 20% EGR and were compared with neat Diesel	Hydrogen with diesel (no EGR) has best BTE, but high NOx, when EGR is used in hydrogen diesel, BTE reduces than the former but higher than neat diesel
"Engine performance of optimized hydrogen-fuelled Direct injection engine" (2013) IJESR [3]	Yadav Vinod Singh, Soni S.L., Sharma Dilip	Kirlosker, 1500 rpm, CR 16.5:1, The injection timing and flow rate of hydrogen were varied (80, 120, 150g/hr) to find out optimum values.	23° CA and 20°CA best for neat diesel and hydrogen enriched respectively, hydrogen enriched shows better result.

Effect of VCR, diluents and feasibility of hydrogen in terms of cost

Article	Authors	Experiment /Research	Findings/Conclusion
"Review on effect of varying compression ratio on performance & emissions of diesel engine fueled with bio-diesel"(2013) [4]	Hani Chotai	Effects of CRs on engine fueled with diesel, blend of diesel with biodiesel and purely on biodiesel with a view to provide a platform for comparison of the parameter	In terms of BTE, BSFC, for B100, B20, D100 optimum CRs were 18, 14.5, 17 respectively, whereas for emission CR of 17, 20.6,18 are preferable.
"Hydrogen fueled diesel engine: Performance improvement through charge dilution techniques"(1992) [5]	Mathur H.B., Das L.M.,Patro T. N	Charge diluents(Helium, Nitrogen, water) for improving the performance, percentage hydrogen energy substitution and knock-limited power output	He and N_2 limit knock tendency and nitrogen improves performance too, water induction made hydrogen to substitute up to 66%
"Updated hydrogen production costs and parities for conventional and renewable technologies" (2010) [6]	Lemus Ricardo Guerrero, Duart Jose´ Manuel Martınez	Economic analysis of producing hydrogen from conventional, nuclear and renewable sources during the last eight years and their potential to rule market.	If carbon tax of 50 $ is added to coal gasification, then biomass hydrogen can achieve cost parities by 2030, or even a few years earlier if carbon taxation has high penalties

Process Flow Chart

Experimental accessories and auxiliary arrangements were identified and procured

↓

Experimental set up was modified

↓

Baseline readings of VCR engine fuelled with neat diesel were taken (at a fixed Injection Timing and Injection Pressure) by varying loads and at various CRs (16-20) [1], the optimum CR was achieved in terms of highest BTE and least BSEC

↓

Same procedures were followed for hydrogen enriched fuel (at a constant flow rate mass/hour basis) and the results were compared

↓

Other parameters like IMEP, BMEP, FMEP, IP, BP, FP, P-V diagram, EGT, volumetric efficiency were also observed and compared.

Engine specifications

PRODUCT	
Make	Apex innovations
Model	Research Engine test setup (240 PE), VCR (computerized)
Engine	
Make	Kirloskar Oil Engines
Model	TV1
No. of cylinder	1 (single)
Bore x Stroke	87.5 X 110 (mm)
Capacity	661 cc
Diesel mode (Rated Output)	3.5 kW
Compression Ratio range	12-22
Rated Speed (constant)	1500 rpm (varies from min 1200-max 2000rpm)
Injection Timing Variations	0^0-25^0 BTDC
Peak pressure	77.5 kg/cm^2
Direction of rotation	Clockwise (from flywheel end side)
Valve timing	IVO 4.5^0 BTDC IVC 35.5^0 ABDC EVO 35.5^0 BBDC EVC 4.5^0 ATDC

Lubrication system	**Forced feed system**
Lubrication oil pump	Gear type
Eddy current Dynamometer	
Model	AG10
Make	Saj Test Plant Pvt. Ltd.
End flanges both side	Carbon shaft model 1260 type A
Connecting Rod length	234 mm
Water inlet	1.6 bar (Water cooling)
Minimum kPa	160 kPa
Continuous current	5 A
Load	3.5 kg (with loading unit)
Speed max.	10000 rpm
Range	Upto 400 kW
Propeller shaft	With universal joints
Fuel tank	Capacity 15 l, fuel metering pipe of glass
air box	M.S. fabricated with orifice and manometer
Calorimeter type	Pipe in pipe
ECU	PE3 Series ECU, Model PE3-8400P
Pump	Type monoblock
Rotameter	Engine cooling 40-400 LPH, Calorimeter cooling 25-250 LPH
Load sensor	Load cell, strain gauge type, range 0-50 kg
Software	”Enginesoft” Engine performance analysis software

Assumptions during experimentation

- Combustion Parameters were assumed to be constant; increase in the parameters with temperature and pressure has been neglected.
- Ambient temperature was assumed as 27^0C
- Geometrical variations were neglected.

Assumed values

Parameters	Value
Specific Gas Constant	1 kJ/kg K
Air Density	1.17 kg/m^3
Adiabatic Index	1.41
Polytropic Index	1.28
Diesel Fuel Density	830 kg/m^3
Calorific Value of diesel	42000 kJ/kg
Calorific Value of hydrogen	
Geometrical Parameters	Value
Orifice Diameter	20 mm
Orifice Coefficient of discharge, C_d	0.60
Dynamometer Arm Length	185 mm
Fuel Pipe diameter	12.40 mm
Pulses Per revolution	360

Methodology

Hydrogen cylinder details

Hydrogen was supplied with the air to the engine at a pressure **0.2 bar(2.5** psi) from a high pressure cylinder (150 bar) with pressure regulator.

Flow rate was measured by **gravimetric method** (measuring the weight of the cylinder) at **40 gm/hour.**

Experimental set up

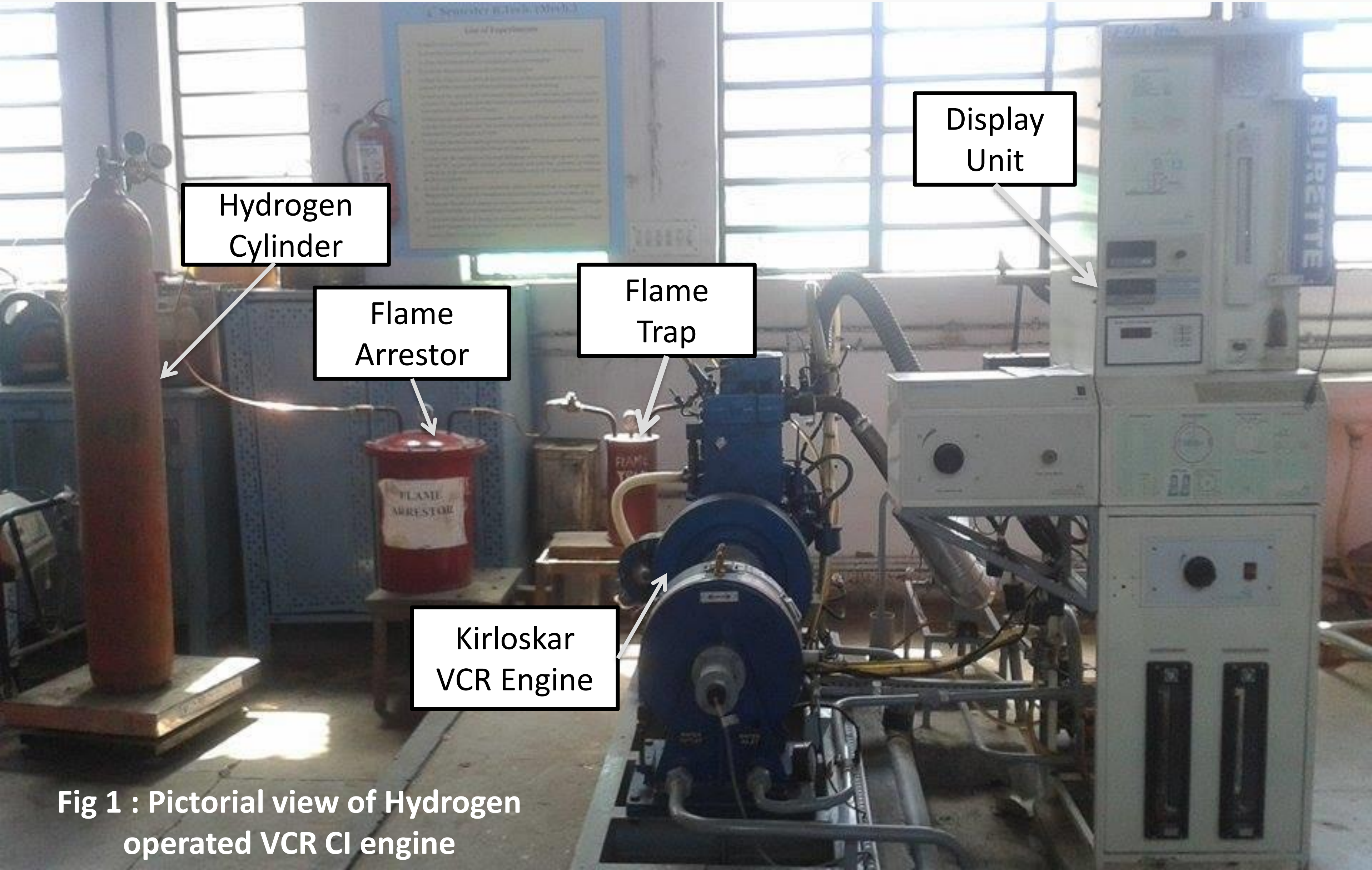


Fig 1 : Pictorial view of Hydrogen operated VCR CI engine

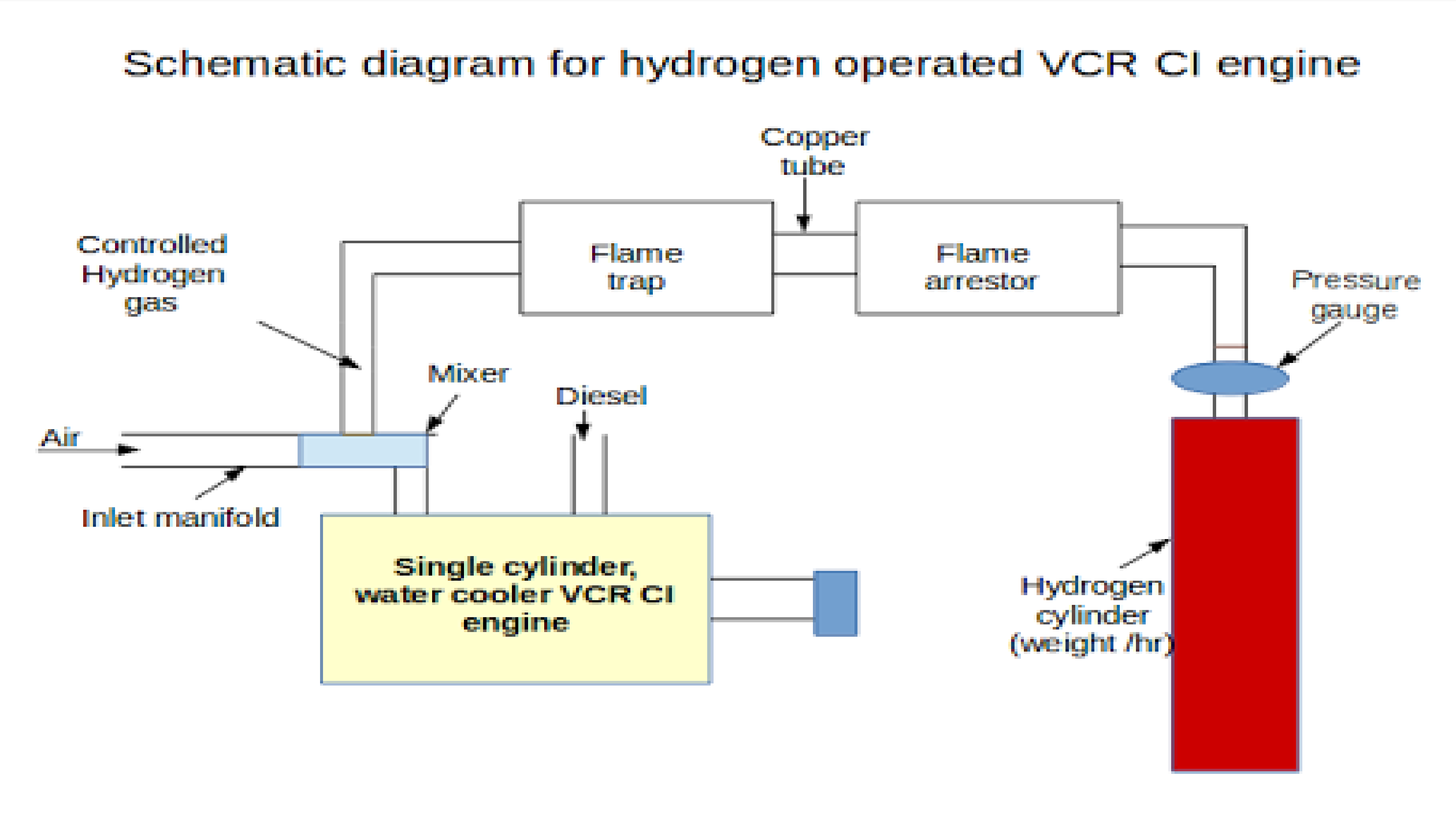


Fig 2: Schematic Experimental set up for hydrogen operated diesel engine

Auxiliary Tools Required

1. Pressure gauge

2. Mixer

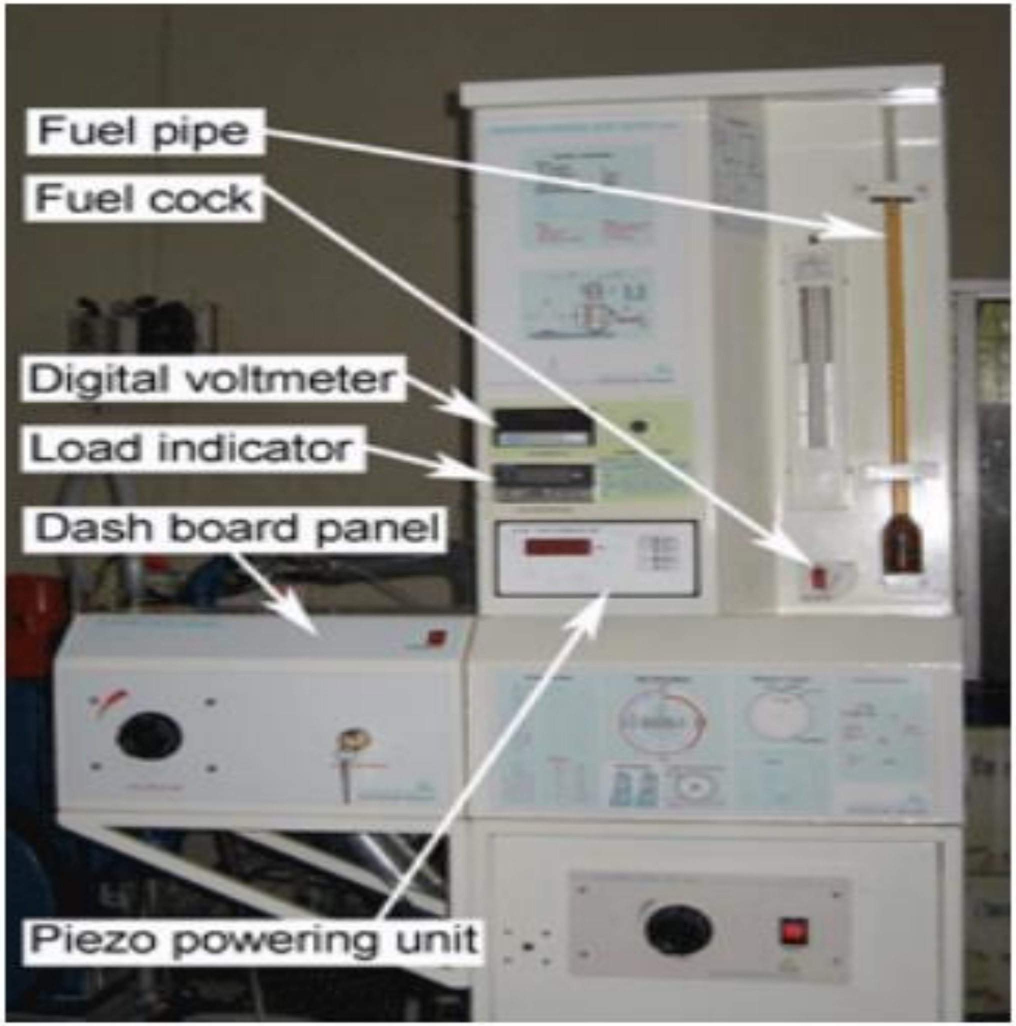
3. Ferrule

4. Copper Pipe bender

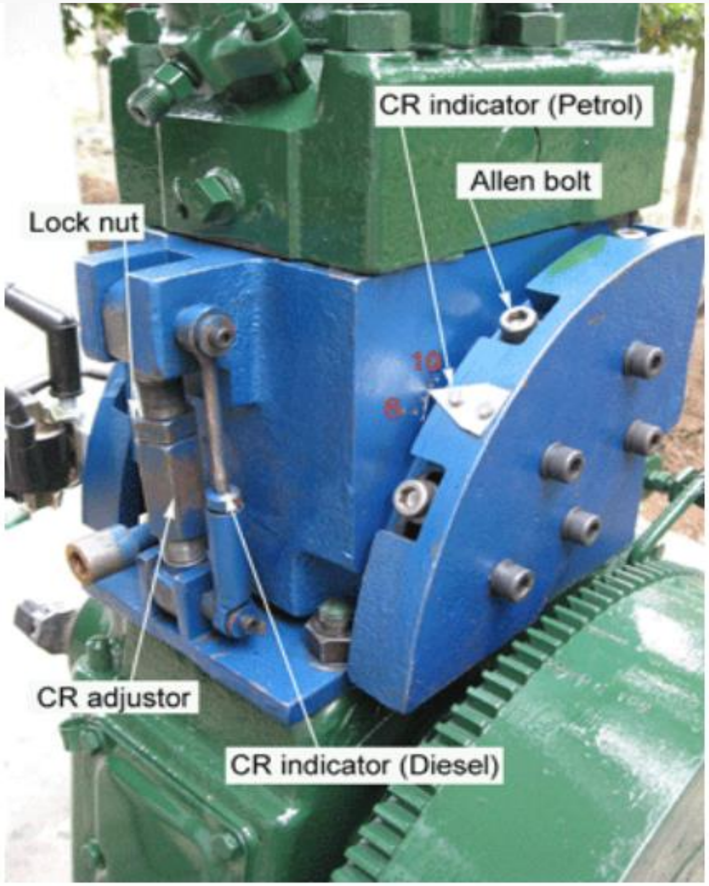
5. Pipe cutter

6. Flame trap and Flame Arrestor

Engine Set Up



Display units



CR adjustor

Test Conditions

Engine was operated at no load and various loads of 2.5 kg, 5 kg, 7.5 kg and 10 kg at each compression ratio from 16-22.

- **100% diesel**

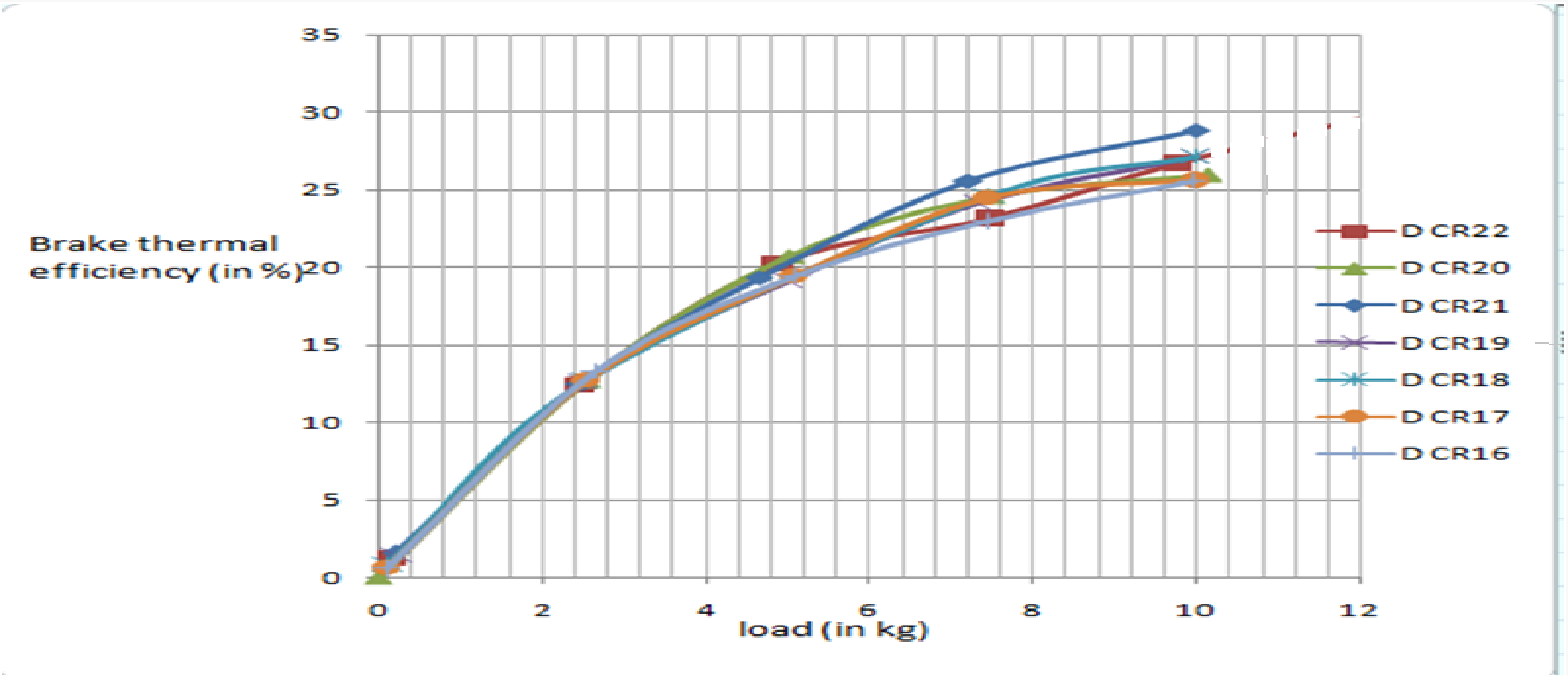
Injection pressure: 195 bar, injection timing 21^0 BTDC, speed constant 1500 rpm, Compression ratio varied from 16-22

- **Blend of diesel and hydrogen fuel**

Injection pressure: 195 bar, injection timing 21^0 BTDC, speed constant 1500 rpm, Compression ratio varied from 16-22

Results and Discussion

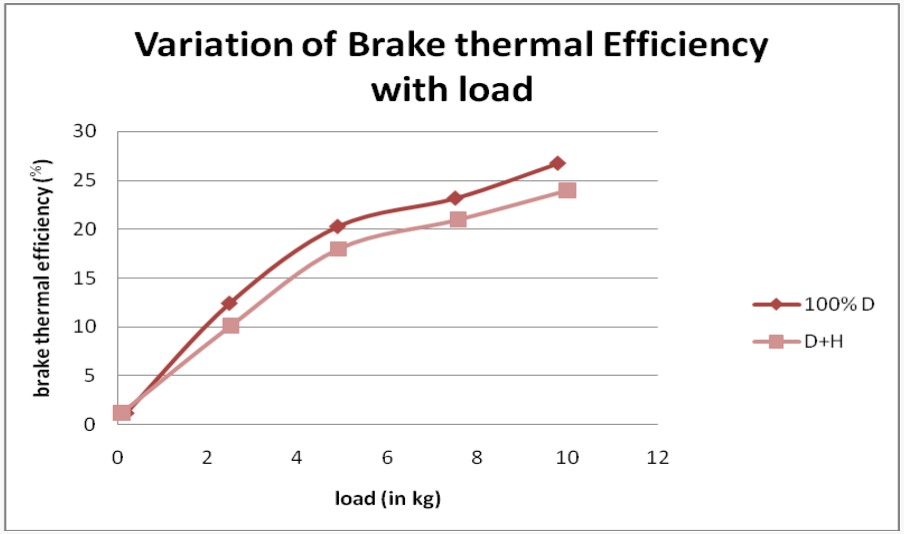
Effect on Brake Thermal Efficiency (BTE)



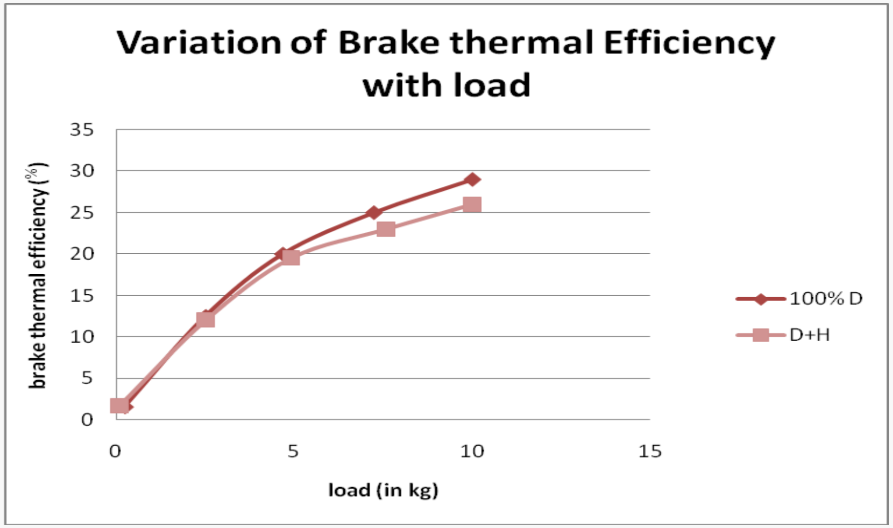
BTE v/s Load with 100% diesel at different **Compression Ratios (16-22)**

Maximum BTE (28.86%) was found to be highest at CR 21 and least BTE was obtained at CR 16. The reason may be at low CR, higher knocking may occur due to longer ignition delay.

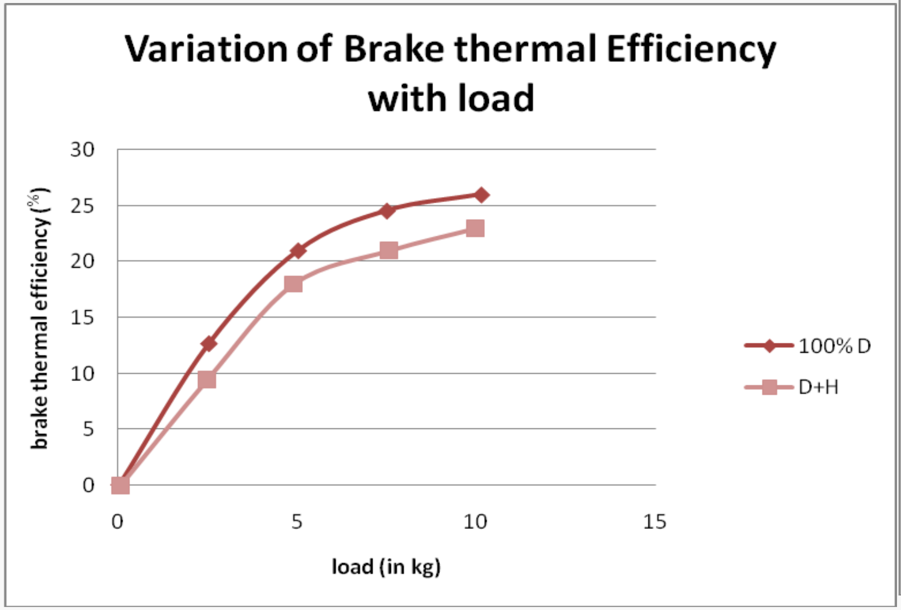
BTE: Brake Thermal Efficiency
CR : Compression Ratio
D: Diesel (baseline reading)



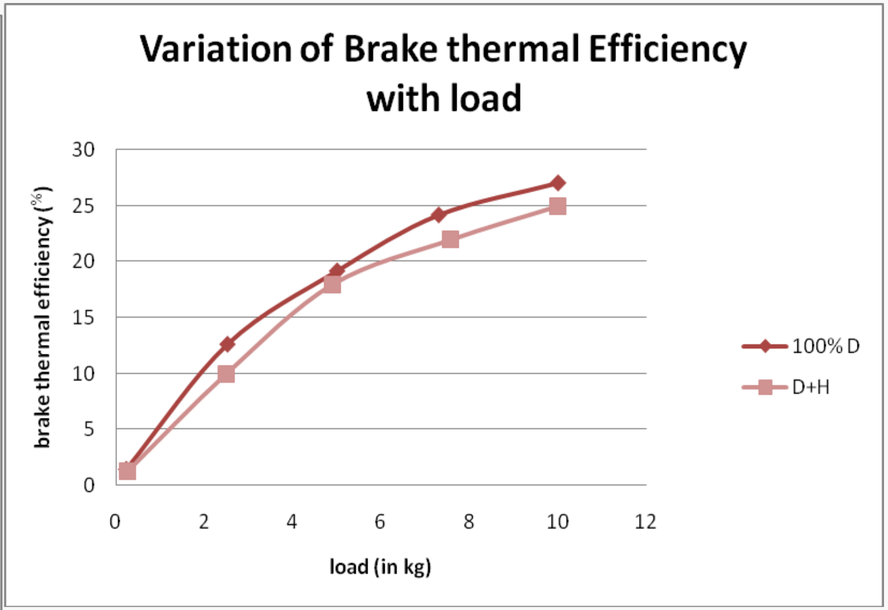
BTE v/s Load (CR 22)



BTE v/s Load (CR 21)

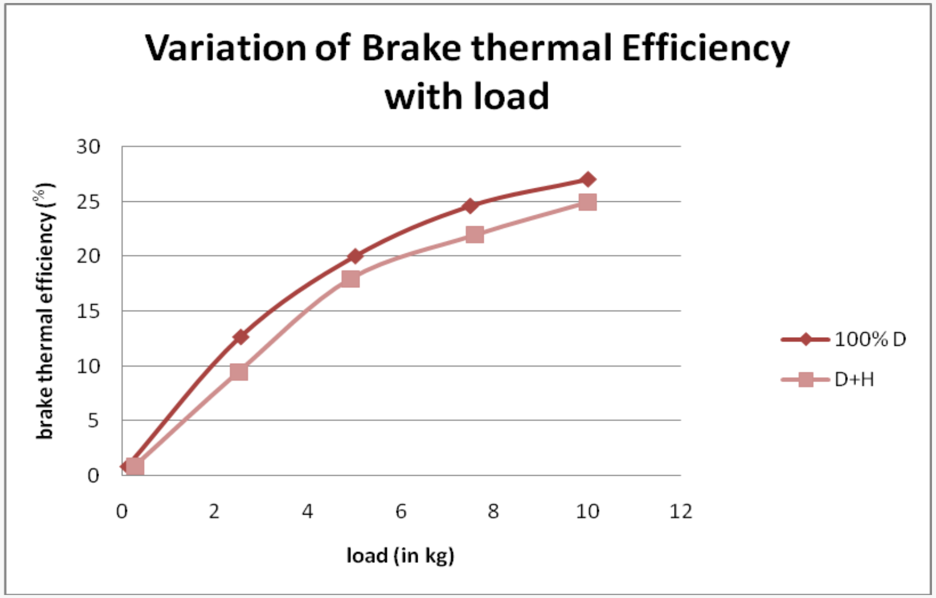


BTE v/s Load (CR 20)

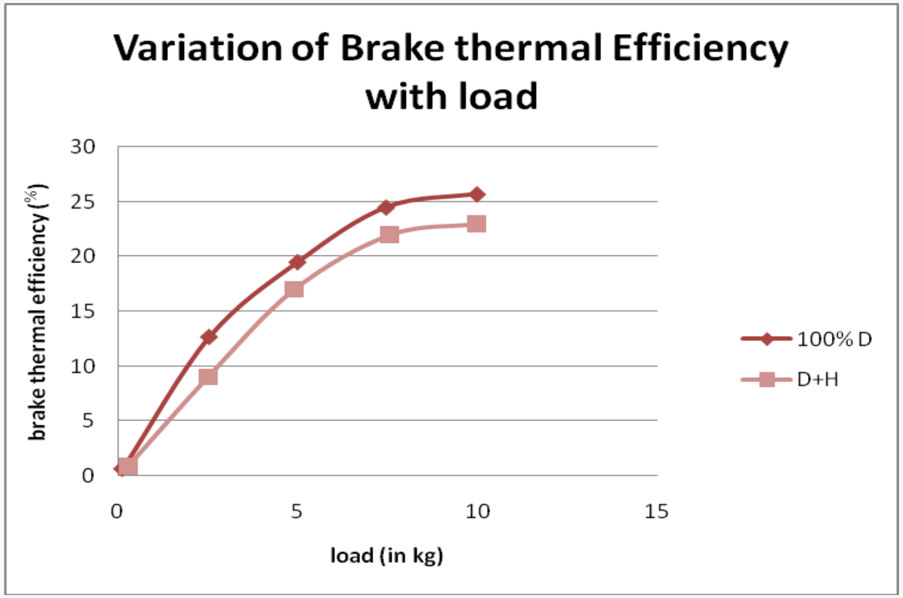


BTE v/s Load (CR 19)

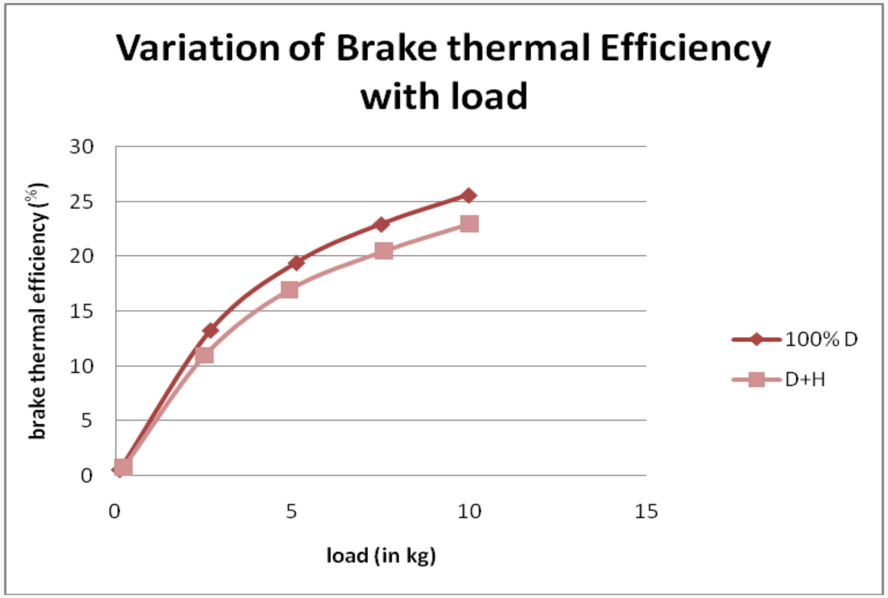
BTE of hydrogen was found slightly lower than neat diesel condition. Maximum BTE with hydrogen was also achieved at CR 21 (26%)



BTE v/s Load (CR 18)



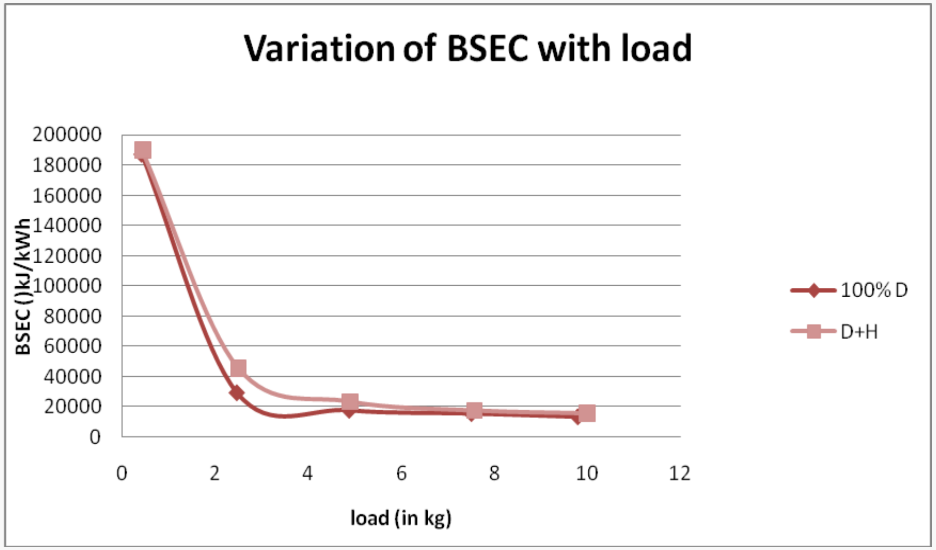
BTE v/s Load (CR 17)



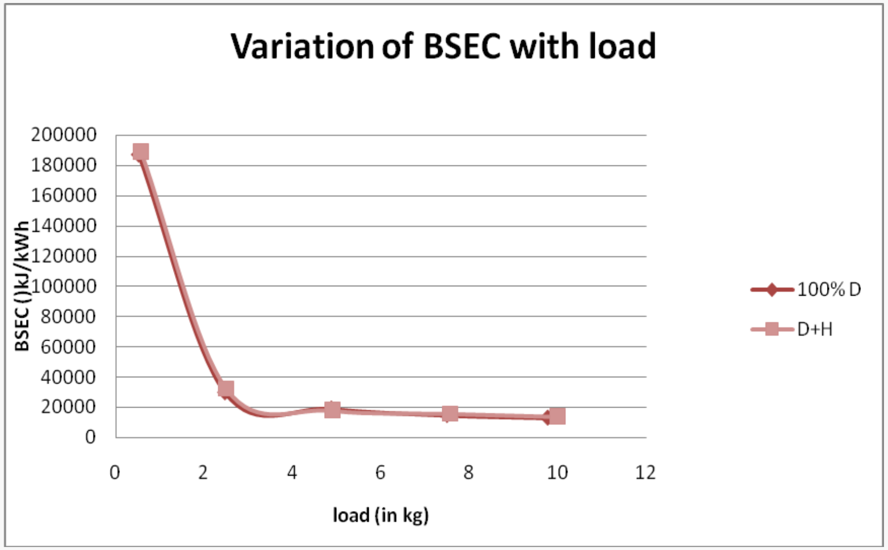
BTE v/s Load (CR 16)

BTE of hydrogen was found lower than neat diesel condition at all compression ratios (16-22).

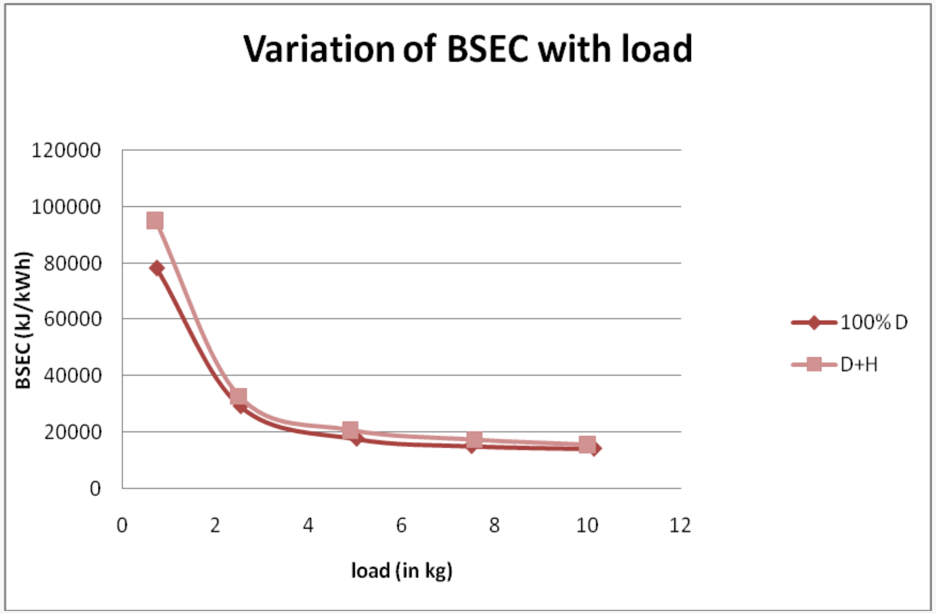
Effect on Brake Specific Energy Consumption (BSEC)



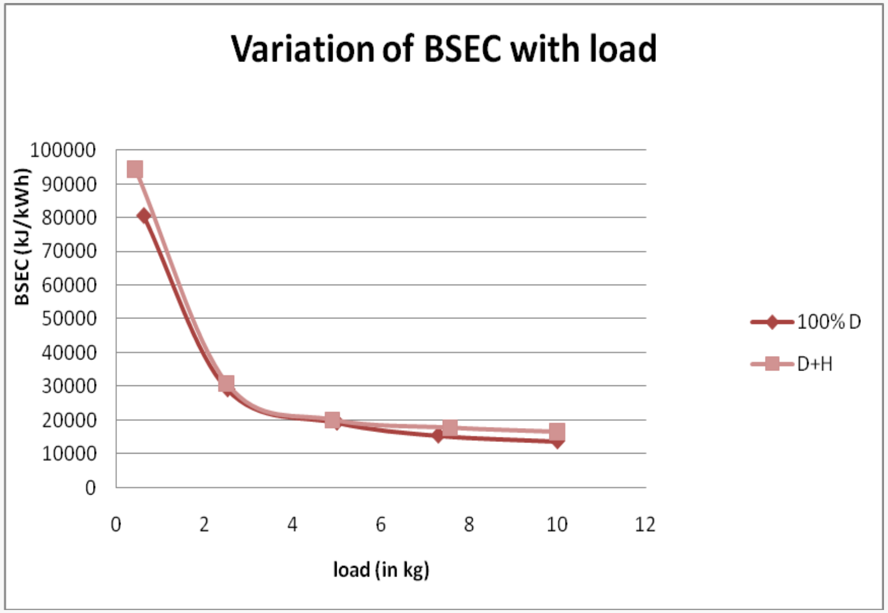
BSEC v/s Load (CR 22)



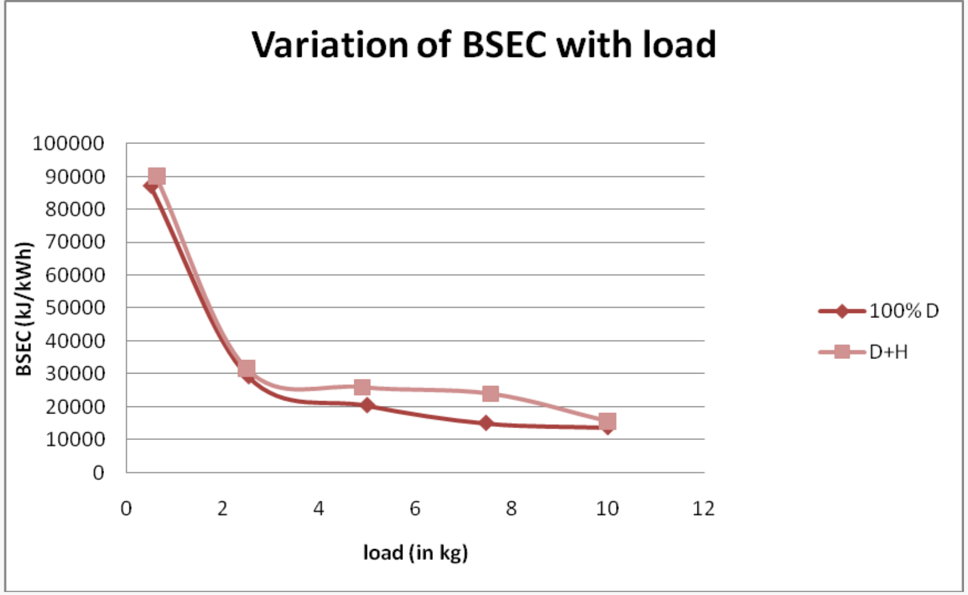
BSEC v/s Load (CR 21)



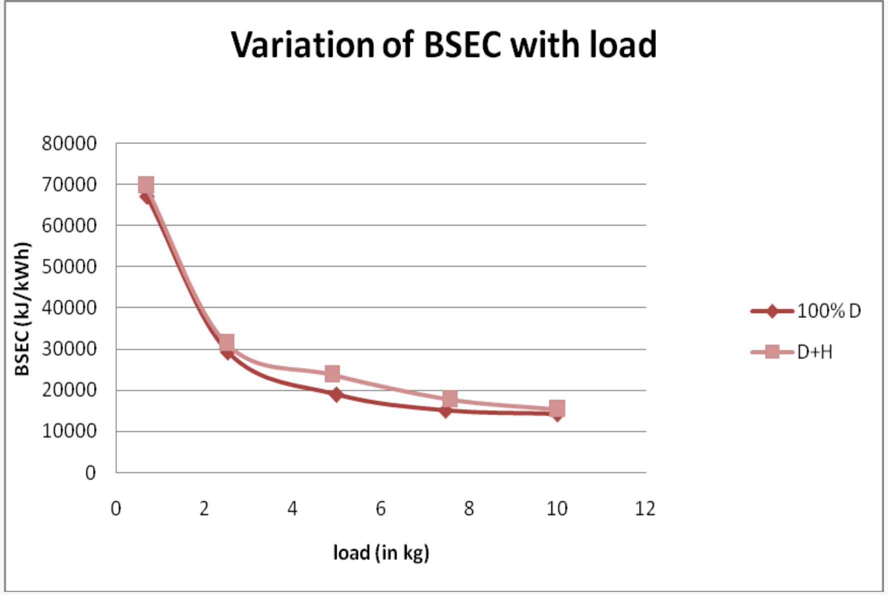
BSEC v/s Load (CR 20)



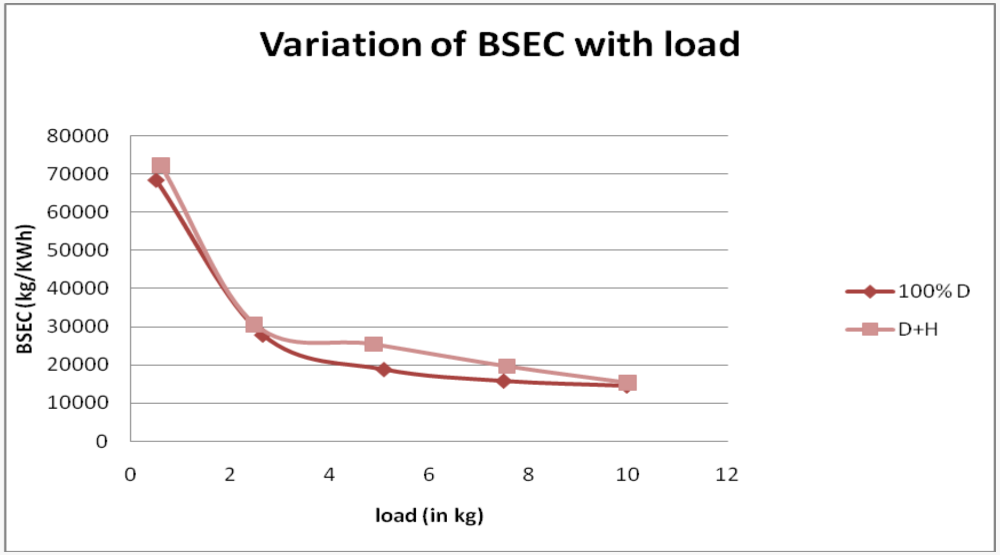
BSEC v/s Load (CR 19)



BSEC Load v/s (CR 18)



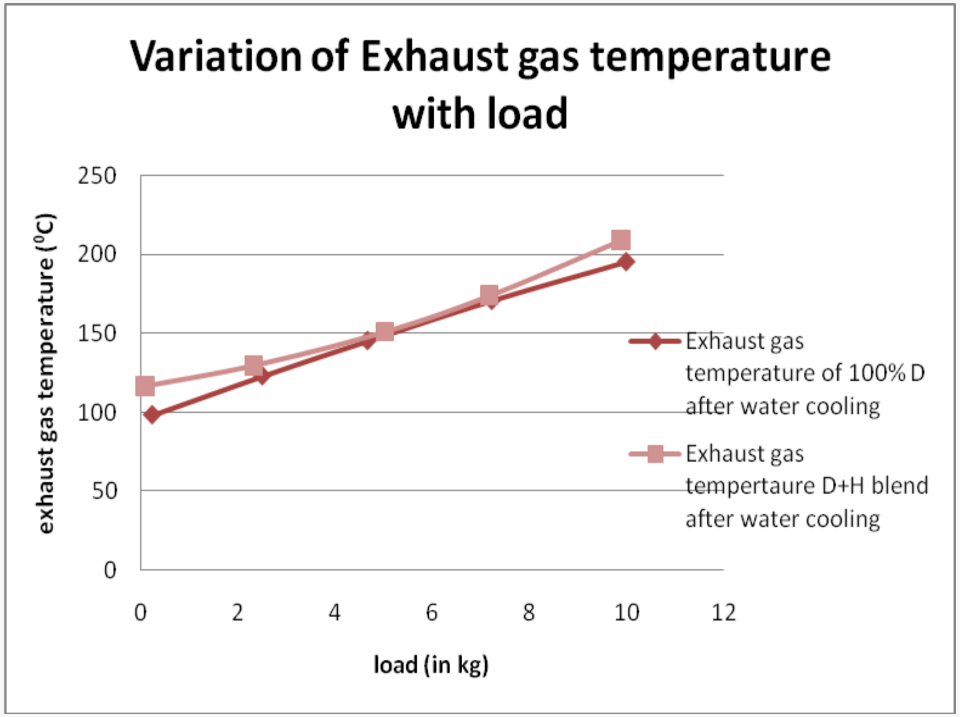
BSEC v/s Load (CR 17)



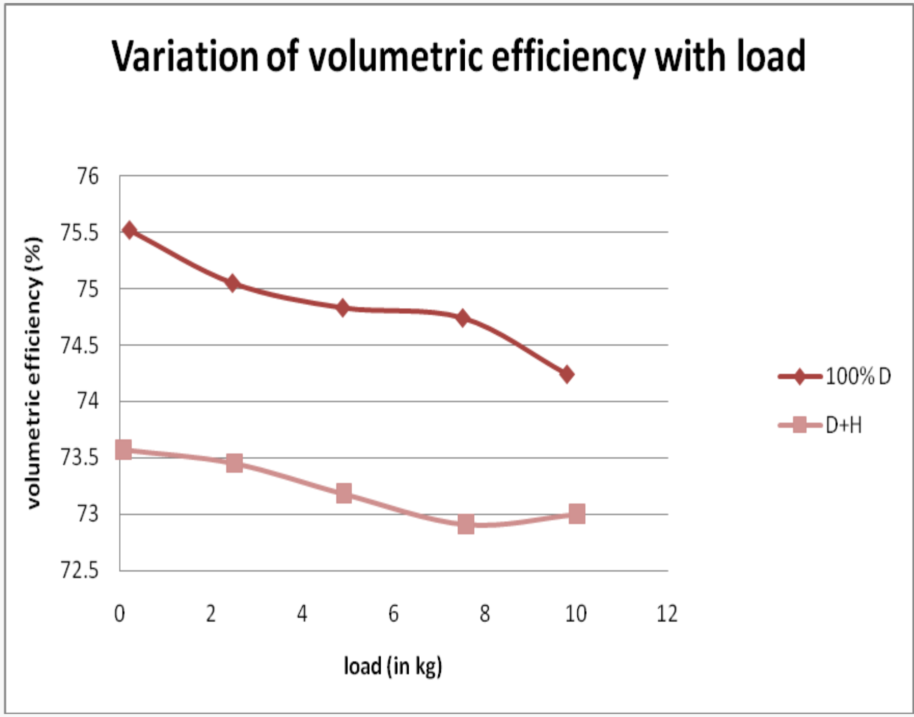
BSEC v/s Load (CR 16)

BSEC was higher in case of hydrogen enriched diesel fuel as compared to neat diesel. Least BSEC obtained at CR 21 for both the cases.

Performance Parameters (CR 21)



Exhaust Gas Temperature (EGT) v/s. Load

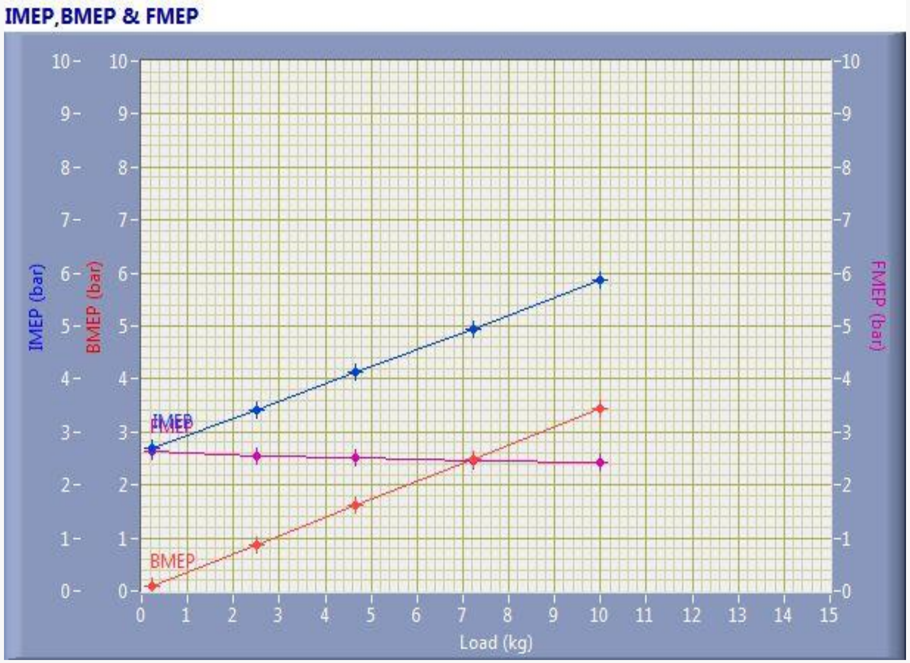


Volumetric efficiency v/s. Load

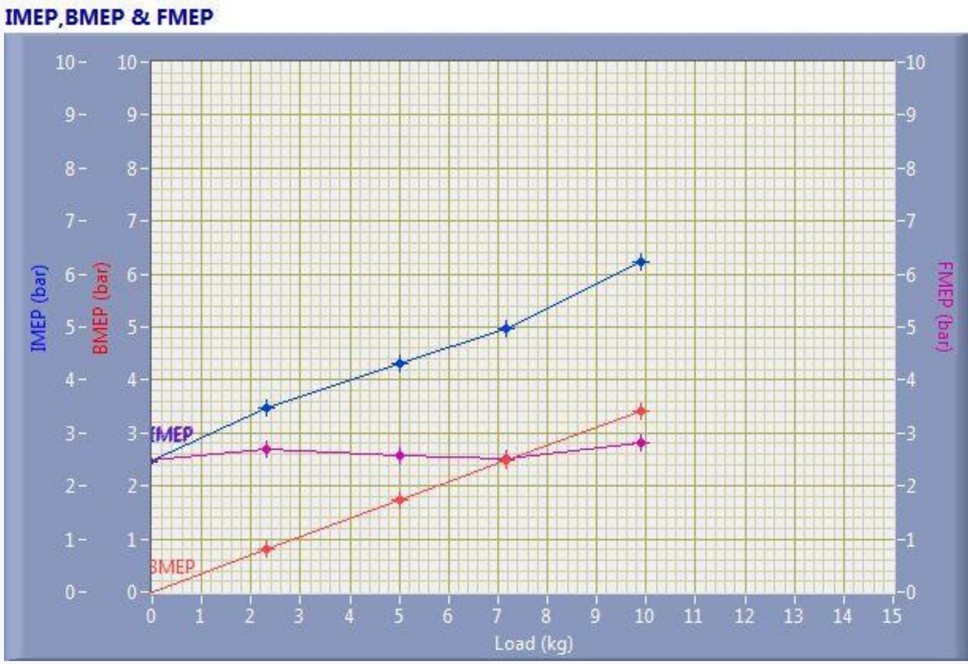
EGT for D+H blend was higher than neat diesel, this may be due to the higher power produced by hydrogen enriched fuel, leading to the production of NO_x

Volumetric efficiency for hydrogen enriched diesel fuel was lower as hydrogen is aspirated along with the air in engine reducing the volumetric air flow

Comparison of IMEP, BMEP and FMEP
(CR 21)



with 100% D



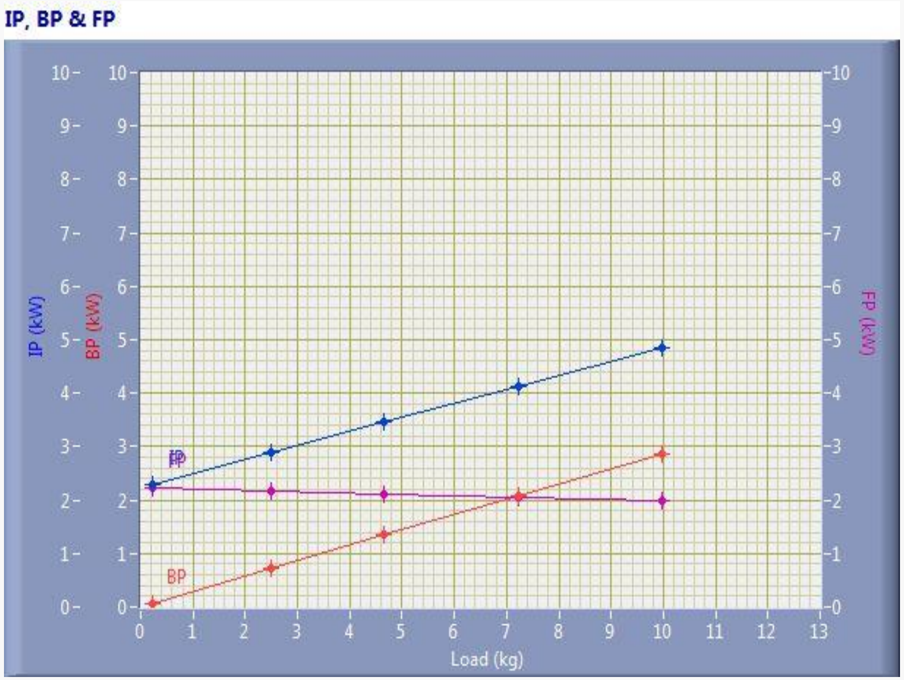
with H+D blend

Higher Mean Effective Pressure (MEP) were obtained in H+D blend resulting in lower ignition delay due to higher charge temperature and greater power is produced.

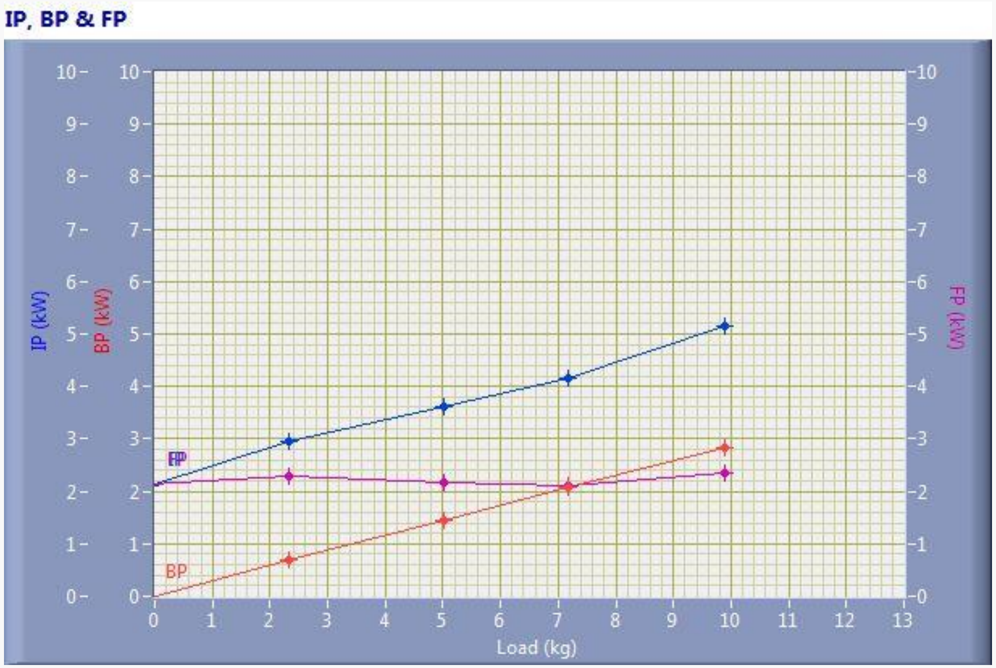
IMEP: Indicated Mean Effective Pressure
BMEP: Brake Mean Effective Pressure
FMEP: Frictional Mean Effective Pressure

[Graphs produced by software “Enginesoft”]

Comparison of IP, BP and FP (CR 21)



with 100% D



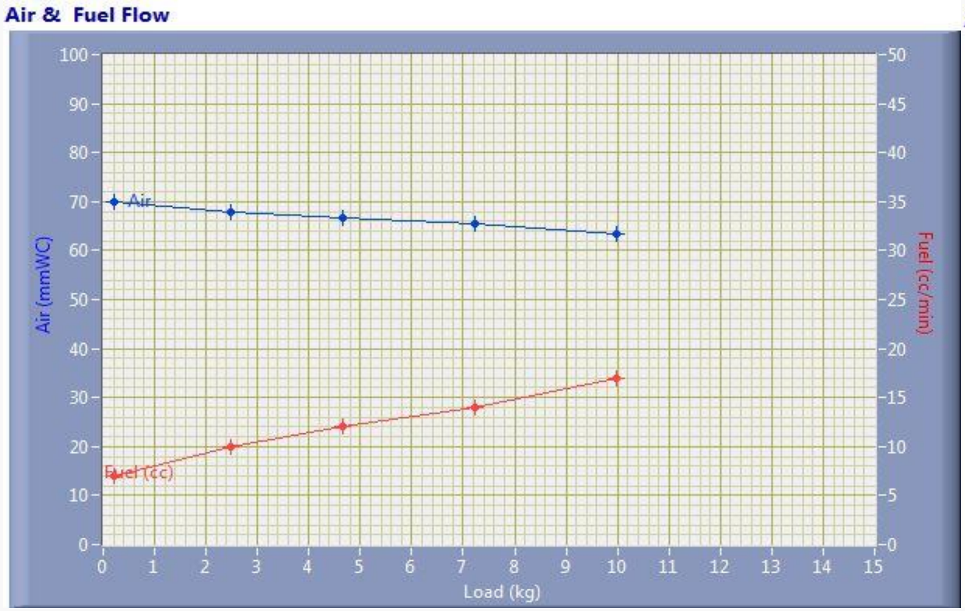
with H+D blend

Higher MEP were obtained in H+D blend resulting in higher power production. IP and FP is found to be significantly higher, this may be because of higher power produced by H+D blend but the effect may have been nullified as mechanical losses are high, leading to higher FP and the BP produced is slightly higher than that of neat diesel.

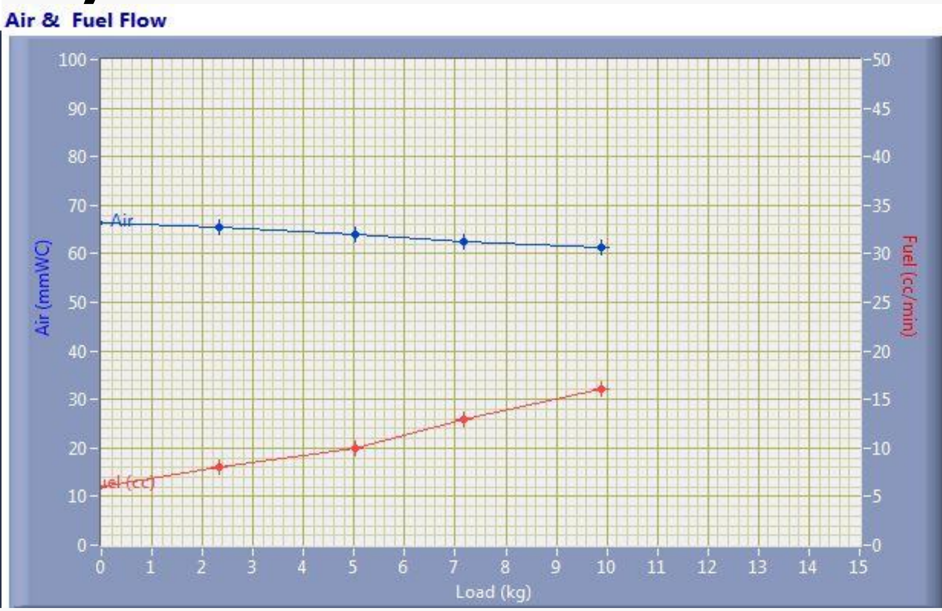
[Graphs produced by software "Enginesoft"]

Comparison of Air and fuel flow

(CR 21)



with 100% D

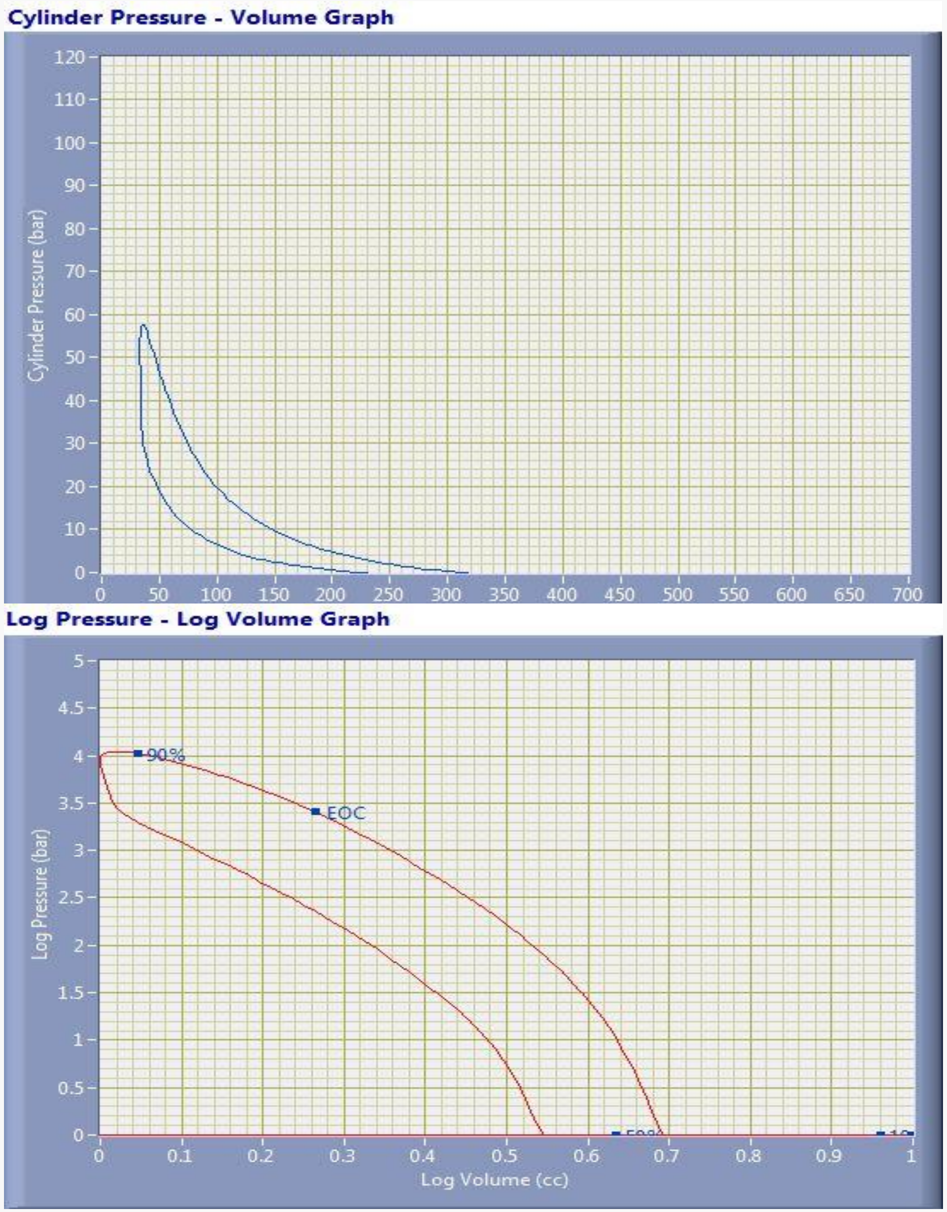


with H+D blend

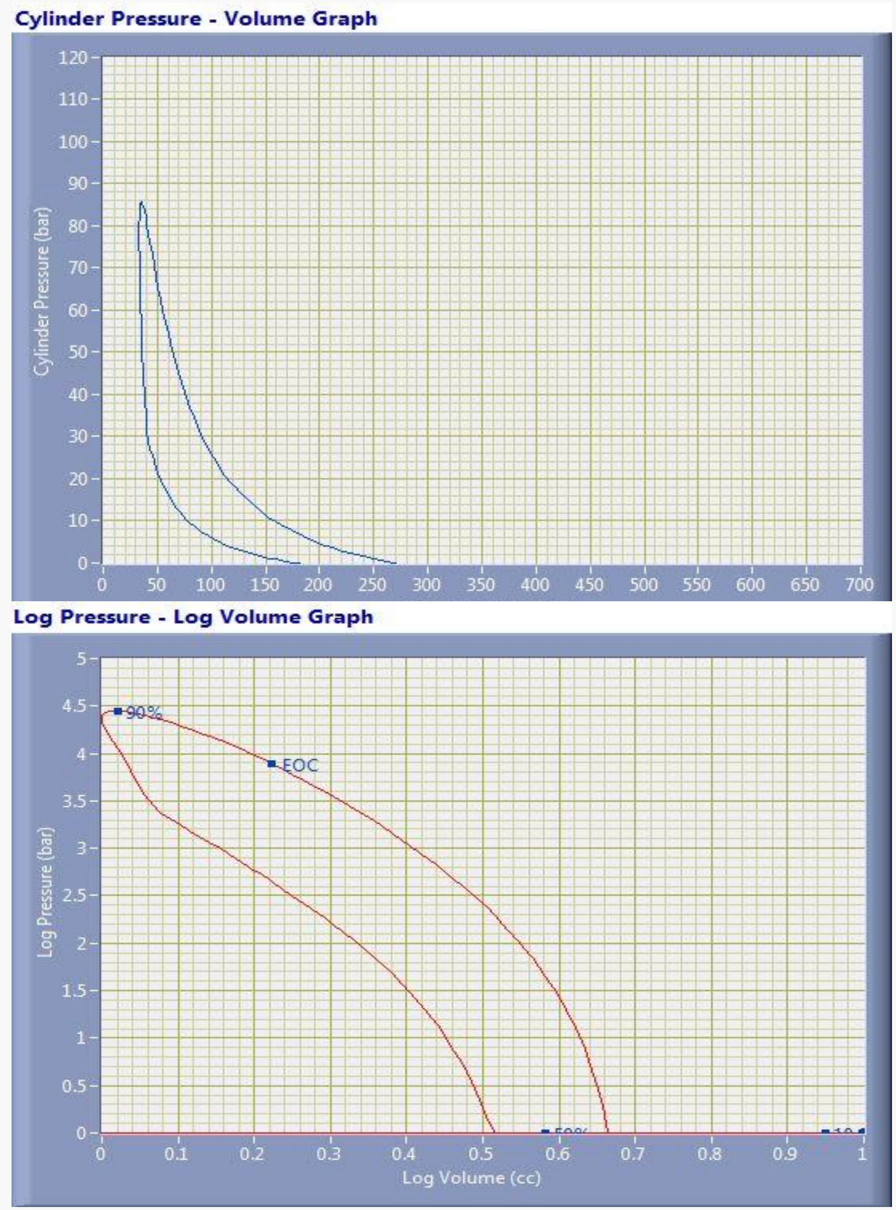
Air and fuel flow both was observed lower with H+D blend, this proves that hydrogen is taking part and supplying heat, reducing the diesel fuel flow rate by 5.88% (Vol. basis) and air flow rate gets reduced by 3.30% (mmWc)

[Graphs produced by software “Enginesoft”]

Comparison of P-V diagram (CR 21)



with 100% D

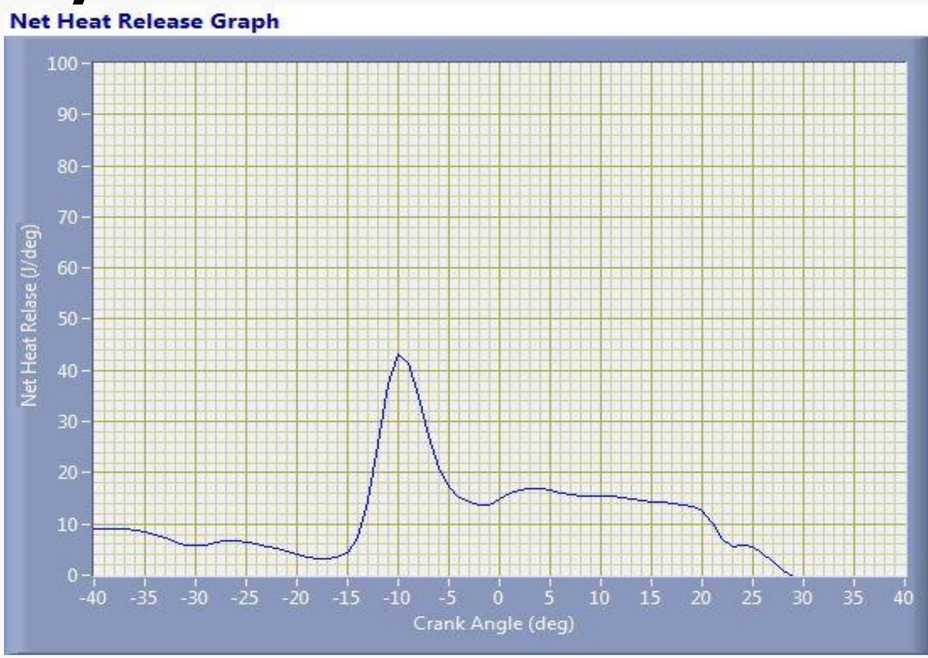


with H+D blend

[Graphs produced by software "Enginesoft"]

Comparison of Net Heat Release graph (CR 21)

with 100% D

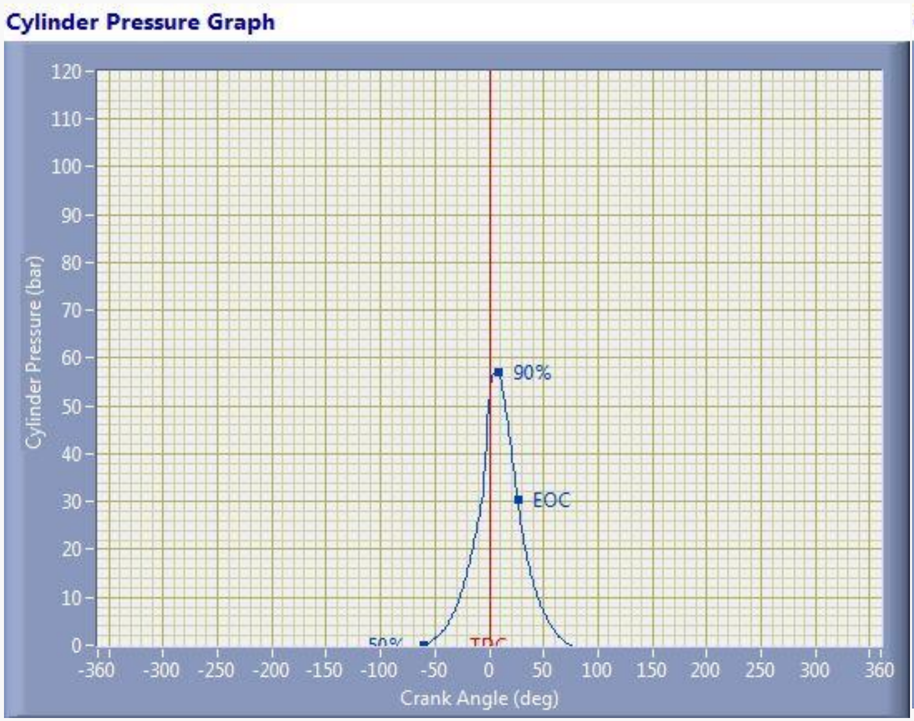


with H+D blend

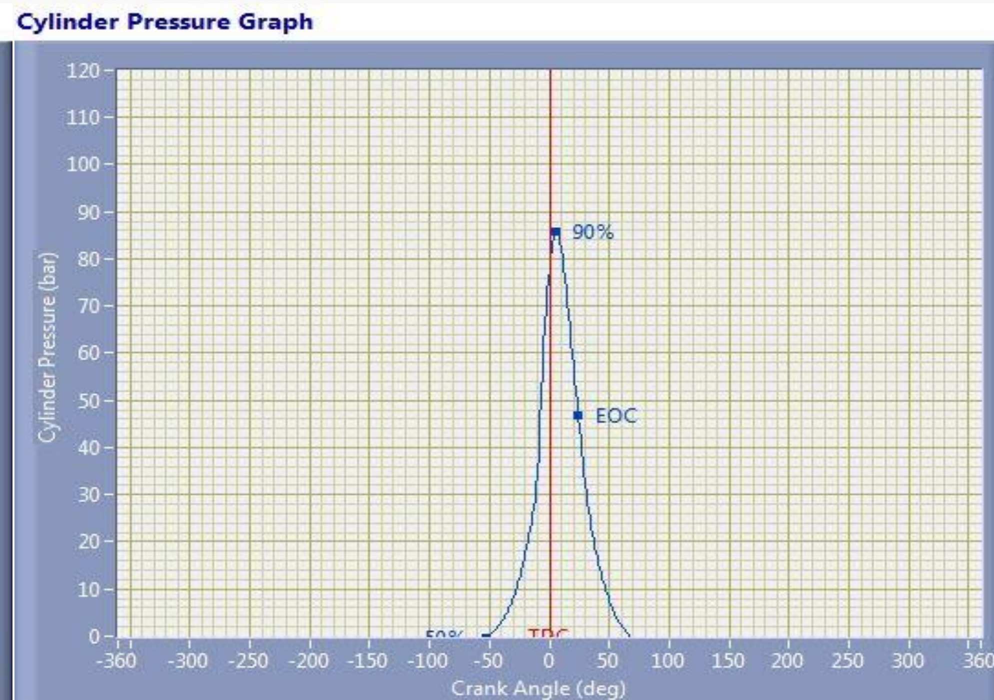
Ignition delay was found to be lower in case of hydrogen enriched diesel and high heat was released by the blend resulting in chances and high heat was released at late combustion phases too. Even though the delay period was low, but high heat was released, this may be due to the fact that complete combustion took place with hydrogen enriched fuel.

[Graphs produced by software “Enginesoft”]

Comparison of P-ϴ graph
(CR 21)



with 100% D

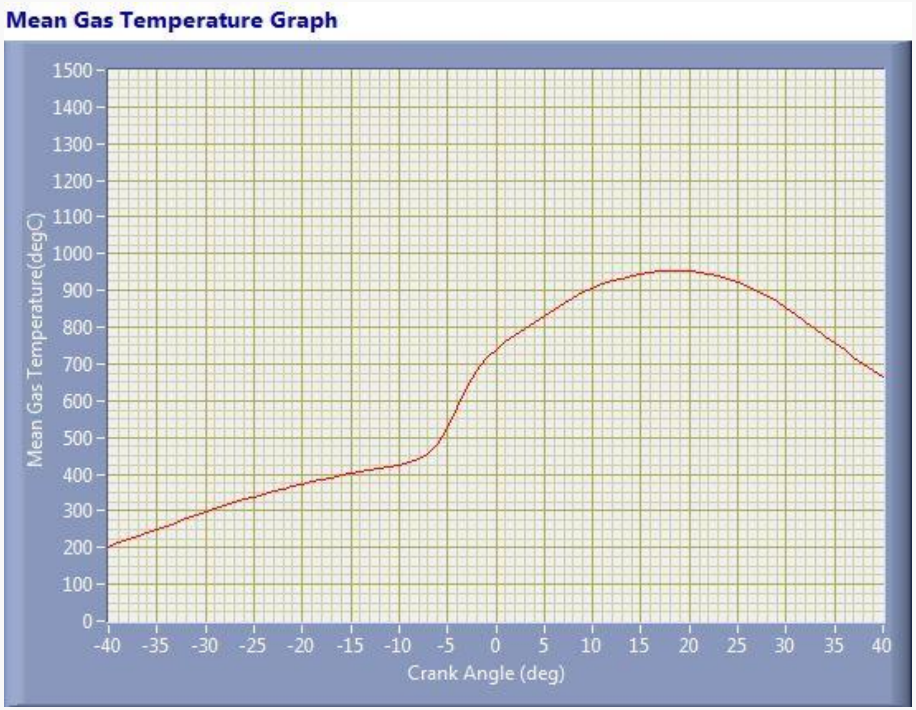


with H+D blend

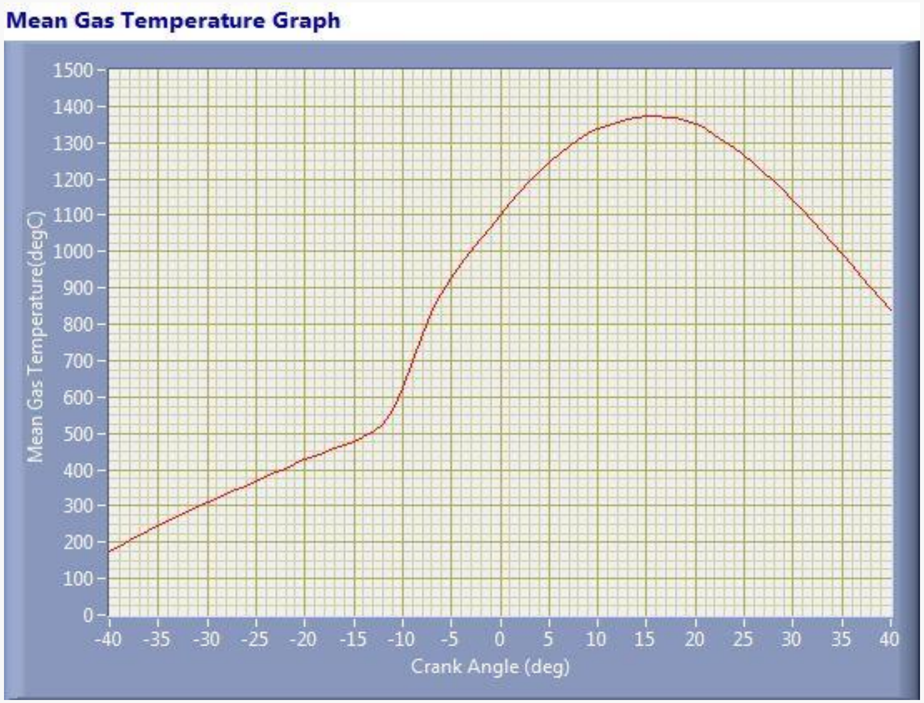
Hydrogen enriched fuel exhibited higher cylinder pressure, this may be due to complete combustion and even in the late combustion phases, the cylinder pressure remained significantly higher

[Graphs produced by software "Enginesoft"]

Comparison of Cylinder mean gas temperature graph
(CR 21)



with 100% D



with H+D blend

Cylinder mean gas temperature was also found higher in case of hydrogen enriched fuel due to proper combustion as compared to neat diesel, this may be caused by higher Calorific Value of hydrogen

[Graphs produced by software “Enginesoft”]

Conclusion

- Compression ratio 21 was found to be the best in terms of highest BTE and least BSEC.
- Highest BTE when operated with diesel was found to be 28.68% at CR 21 and when the engine was run with hydrogen enriched diesel fuel at the same operating conditions, then the highest BTE was obtained as 26% (considering the heat supplied by the hydrogen fuel).
- It was observed that when the fuel is enriched with hydrogen, there is a decrease in diesel fuel consumption by 5.88% (volume basis). However, there is a reduction in air flow rate by 3.30% (mmWc basis) and 1.67% (volume basis) as hydrogen is aspirated with engine’s intake air.
- Rise in cylinder pressure, and mean gas temperature of cylinder was found to be higher in hydrogen-diesel blend which leads to the increase in compressive stresses inside the engine cylinder.

Publications

- <u>International Conference</u>

1. ***Debasmita Bal***, S.L. Soni, Dilip Sharma, Anmesh K Srivastava, Ramesh K. Meena "A Design methodology of solar assisted air conditioning system for a particular location", ICRTME 2015, 25th -26th March'15 VIT Jaipur, **awarded** with "**Best Technical Paper"** in Technical session of *Energy Engineering and Sustainable development*
2. ***Debasmita Bal*** ,S.L. Soni, Dilip Sharma, Deepesh Sonar, Saurabh Kumar, "Use of Hydrogen as an energy source in diesel engines State of the art: A review", ICEE, 15-17th Dec 2014, JNTU, Hyderabad
3. S.L. Soni, Dilip Sharma Saurabh Kumar, ***Debasmita Bal***, "Possibility to use hydrogen obtained from water electrolysis as a fuel additive in a vehicle and its integration with energy recovery technologies", ICEE, 15-17thDec 2014, JNTU, Hyderabad

- <u>International Journal</u>

1. **Debasmita Bal**, S. L. Soni, Dilip Sharma, "Exhaust heat utilization for comfortable cabin conditions of CI engine: A review", IJTRE , ISSN (online) 2347-4718, Vol: 2, Issue 1, Sept 2014

References

1. Szwaja Stanislaw, Grab-Rogalinski Karol, "*Hydrogen combustion in a compression ignition diesel engine*", ***Elsevier*,** International Journal of Hydrogen Energy 34 (2009) pp. 4413-4429

2. Yadav Vinod Singh, Soni S.L., Sharma Dilip, "*Performance and emission studies of direct injection C.I. engine in duel fuel mode (hydrogen-diesel) with EGR*", ***Elsevier*,** International Journal of Hydrogen Energy 37 (2012) pp. 3807-3817

3. Singh Yadav Vinod, Soni S. L. and Sharma Dilip, *"Engine performance of optimized hydrogen-fuelled Direct injection engine",* International Journal of Scientific & Engineering Research (**IJSER),** (Vol: 4) Issue 6, June-2013, ISSN 2229-5518

4. Hani Chotai , "*Review on effect of varying compression ratio on performance & emissions of diesel engine fueled with bio-diesel*", **International Journal of Engineering Science and Innovative Technology** (**IJESIT**) Volume 2, Issue 4, July 2013, ISSN: 2319-5967

5. Mathur H.B., Das L.M.,Patro T. N., *"Hydrogen fueled diesel engine: Performance improvement through charge dilution techniques*" ***Elsevier*, International Journal of Hydrogen Energy**, Vol: 18 (5) (1992) pp. 421-431

6. Lemus Ricardo Guerrero, Duart Jose´ Manuel Martınez, "*Updated hydrogen production costs and parities for conventional and renewable technologies*", ***Elsevier*, International Journal of Hydrogen Energy** 35 (2010) pp. 3929-3936

7. Edutekindia.com/**VCR engine set up**

Thank you

Annexure (CR 21)

Tabular comparison of Diesel and Diesel+ Hydrogen

Diesel + 0%Hydrogen

Air Flow (kg/h)	Fuel Flow (kg/h)	SFC (kg/kWh)	A/F Ratio	HBP (%)	HJW (%)	HGas (%)	HRad (%)
27.22	0.35	5.45	78.07	1.57	85.40	21.60	0.00
26.80	0.50	0.69	53.82	12.49	72.05	20.33	0.00
26.56	0.60	0.44	44.45	19.35	67.34	20.94	0.00
26.36	0.70	0.34	37.81	25.55	63.30	22.03	0.00
25.96	0.85	0.30	30.66	28.84	56.71	21.50	0.00

Diesel + Hydrogen

Air Flow (kg/h)	Fuel Flow (kg/h)	SFC (kg/kWh)	A/F Ratio	HBP (%)	HJW (%)	HGas (%)	HRad (%)
26.55	0.30	0.00	88.85	0.60	90.85	18.14	0.00
26.33	0.40	0.59	66.09	14.63	83.81	27.63	0.00
26.03	0.50	0.34	52.27	25.08	79.25	27.27	0.00
25.75	0.65	0.31	39.77	27.36	69.51	25.09	0.00
25.52	0.80	0.28	32.03	30.36	63.36	25.63	0.00

Tabular comparison of Diesel and Diesel+ Hydrogen

Diesel + 0%Hydrogen

Torque (Nm)	BP (kW)	FP (kW)	IP (kW)	BMEP (bar)	IMEP (bar)	BTHE (%)	ITHE (%)	Mech Eff. (%)
0.39	0.06	2.24	2.30	0.07	2.70	1.57	56.53	2.78
4.52	0.73	2.16	2.89	0.86	3.42	12.49	49.72	25.12
8.46	1.35	2.11	3.46	1.61	4.12	19.35	49.61	39.01
13.11	2.08	2.05	4.13	2.49	4.95	25.55	50.77	50.32
18.12	2.85	2.00	4.85	3.44	5.86	28.84	49.06	58.78

Diesel + Hydrogen

Torque (Nm)	BP (kW)	FP (kW)	IP (kW)	BMEP (bar)	IMEP (bar)	BTHE (%)	ITHE (%)	Mech Eff. (%)
0.13	0.02	2.13	2.11	0.02	2.47	0.60	60.41	0.99
4.22	0.68	2.28	2.96	0.80	3.49	14.63	63.61	22.99
9.11	1.46	2.16	3.62	1.73	4.30	25.08	62.26	40.28
13.02	2.07	2.10	4.16	2.47	4.98	27.36	55.11	49.65
17.96	2.82	2.33	5.16	3.41	6.23	30.36	55.48	54.73