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Experimental Analysis of SI Engine Performance and Emission Characteristics with Gasoline-Denatured Spirit Blends as Alternative Fuels

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Abstract – *The experimental study focused on investigating benefits of unleaded gasoline (P100) – denatured spirit [DNS (ethanol 93.3% v/v + water 6.7% v/v)] blends as fuel in a four cylinder four stroke SI engine. Performance tests were conducted to study volumetric efficiency (VolE), brake thermal efficiency (BThE), brake power (BP), engine torque (torque), brake specific fuel consumption (BSFC). Engine exhaust emissions were investigated for carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x) and carbon dioxide (CO_2). Experiments were conducted at different engine speeds between 2500 - 4500 rpm maintaining throttle position of 50% throughout the experiments. The fuel blends used include DNS30P70 (ethanol 28 % + water 2% + gasoline 70 %), DNS50P50 (ethanol 46.65 % + water 3.35 % + gasoline 50 %) and DNS85P15 (ethanol 79.3 % + water 5.7 % + gasoline 15 %) which were compared with base fuel P100. The investigations revealed that blending DNS with P100 increases BThE, VolE, BP, torque and BSFC. The CO, HC, NO_x and CO_2 emissions in the exhaust decrease when compared to P100 operation. The DNS85P15 blend produced encouraging results in improved engine performance and decreased engine exhaust emission.*

Keywords – Alternative fuel, denatured spirit, emission, ethanol, fuel additive.

1. INTRODUCTION

As the world lead to the civilization and advancement in day to day life the need for newer alternatives keep popping up and the resources tend to deplete at a faster rate. Automobile industry is not an exception; the world consumes gasoline fuel to such an extent that today the whole world is exploring new renewable and non polluting fuels**.** Petroleum fuels are stored fuels in earth's crust with limited reserves, and are irreplaceable. The present known reserves of petroleum fuels with the growing rate of consumption are not going to last long. The uneven distribution of petroleum reserves around the world has given rise to frequent disruptions and uncertainties in supply as well as price. Apart from faster depletion and irreplaceable nature of petroleum fuels, another important aspect of their use is the extent and nature of environmental pollution caused by their combustion in vehicular engines. Petroleum fuelled vehicles discharge significant amount of pollutants like CO, HC, NO_x, CO_2, soot and particulates which have adverse effects on the flora and fauna.

Fuel additives to gasoline are identified by several researchers in order to improve the octane rating and performance of fuel in SI engine. Among the additives, oxygenates have shown improved results in SI engine operation. Among oxygenates ethanol, methanol, tertiary butyl alcohol and methyl tertiary butyl ether (MTBE) were a few important additives under consideration [1]. Ethanol is one of a promising alternative fuel for SI engine owing to its high octane rating, leaner flammability limit, higher flame speed, high latent heat of vaporization and renewable nature as mentioned by Yücesu *et al.* [2] in his research article and he conducted experiments on a single cylinder variable compression ratio SI engine to study the performance and exhaust emissions using ethanol – gasoline blends. The fuel blends used were E10, E20, E40 and E60 for six different compression ratios from 8-13. It was found that there was increase in the torque at higher compression ratios. The fuel blends with higher proportion of ethanol (E40 and E60) had considerable effect on reduction of emission. The decrease in HC was considerable as compared to CO. Kameoka *et al.* [3] studied the effect of alcohol fuels on fuel-line materials and reported the corrosion of fuel system components. Latey *et al.* [4] have investigated effect of various methanol – ethanol gasoline blends (M5E5, M5E10, M5E15, M5E20) on single cylinder SI engine and reported an improvement in engine performance with lowered emission. Yüksel and Yüksel [5] used ethanol 60% - gasoline 40% blend in a four cylinder SI engine and concluded that torque output and brake specific fuel consumption of engine increases slightly, CO and HC emission decrease considerably and CO_2 emission increase marginally. Bayraktar [6] experimented with blends in lower proportions of 1.5, 3, 4.5, 6, 7.5, 9, 10.5 and 12% by volume of ethanol and reported that 7.5% ethanol is suitable for engine performance and from CO emission point of view.

Oldberding *et al.* [7] carried out dynamometer tests of ethanol water fueled transit van by replacing the

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conventional ignition system with a catalytic ignition system. It is reported that there was considerable reduction of NO_x and CO emission, marginal decrease in CO_2 emission and increase in thermal efficiency. Jia *et al.* [8] studied effect of E10 on a four stroke motor cycle engine and reported reduction in CO, HC, acetaldehyde and ethylene in exhaust. Maheshwari *et al.* [9] under Ministry of Petroleum and Natural Gas, India sponsored study carried out experiments to investigate effect of 10% ethanol in gasoline and examine its startability, drivability and emission for regulated pollutants without modifications of existing engine components of test vehicles. The results indicated that addition of 5% and 10% ethanol to gasoline increased octane number by 1.3 to 3.4 units respectively. It is also reported that ethanol can substitute Benzene and MTBE as octane boosters presently used in refineries. In startability tests on two wheelers and four wheelers the operations were satisfactory. In mass emission studies two wheelers showed slight increase in HC emissions with 5% and 10 % addition of ethanol, but in case of two wheelers fitted with catalytic converters both HC and CO reduced. In case of four wheelers reduction of both HC and CO was noticed with marginal increase in NO_x.

Al-Hasan [10] through experiments on a four cylinder four stroke SI engine operated on gasoline-ethanol blends investigated engine performance at speeds between 1000 and 4000 rpm. The experiments were conducted at three fourth throttle with 5%-30% of ethanol used in blending with gasoline. The author reported that engine performance improved with gasoline-ethanol blends. Ceviz and Yüksel [11] investigated the coefficient of variation in indicated mean effective pressure (IMEP), CO and HC emission and reported a lower value for 10% ethanol blend. Thus with 10% ethanol blend smoother engine operation was noticed due to least cycle to cycle variations. Maji *et al.* [12] carried out experiments to evaluate engine performance and exhaust emission with ethanol-gasoline blends E85 and E15 in a single cylinder four stroke SI engine. The engine speed, compression ratio (CR), air fuel ratio (A/F), ignition timing and intake air temperature were experimental parameters considered for the study. The maximum power with ethanol blends was achieved near stoichiometric A/F and HC emission was least for E85 blend. The engine performance improved with retarded ignition timing. Intake air heating however did not show any improvement in engine performance with blends. Jeuland *et al.* [13] investigated green house gas emission in their dedicated engine experiment with ethanol as fuel and reported increased engine efficiency with reduction of CO_2 up to 20%. Rudolph and Thomas [14] conducted experiments on SI engine to evaluate engine performance and emission for 10% blends of methanol, ethanol, MTBE and α-methyl tetrahydrofuran (MTHF). The experiments with full throttle position for engine speeds ranging between 2000 and 3200 rpm indicated that MTHF-gasoline blend, with high A/F density products as compared to MeOH-, EtOH- and MTBE-gasoline blends has performance and emission profile similar to gasoline.

Correa *et al.* [15] analyzed the data of acetaldehyde and formaldehyde concentrations at the city of Rio de Janeiro, Brazil which is flooded with gasohol operated vehicles. The results revealed that high ambient levels of acetaldehyde and acetaldehyde / formaldehyde ratio. It was also stated that the acetaldehyde / formaldehyde ratio change depending upon solar flux, vehicular emission and temperature. Topgul *et al.* [16] studied unleaded gasoline-ethanol blends up to E60 and reported benefits of ignition timing retardation for ethanol blends.

Hsieh *et al.* [17] experimented on a commercial 1600 cc GA16DE engine with multi point fuel injection (MPFI) gasoline engine operated on gasoline-ethanol blends. The blends with 0%, 5%, 10%, 20%, and 30% ethanol were investigated and it was reported that torque and BSFC slightly increased with increasing blend ratios. The CO and HC emission decreased drastically and CO_2 emission increased marginally. It was indicated that NO_x is dependent on engine operating conditions but not on ethanol content in fuel. Yücesu *et al.* [18] conducted comparative study of mathematical and experimental analysis of a single cylinder SI engine performance using ethanol-gasoline blends E10 (ethanol 10% + gasoline 90%), E20, E40 and E60. The parameters considered were ignition timing, relative air fuel ratio (RAFR) and CR at a constant speed of 2000 rpm with wide open throttle (WOT) position. The Artificial Neural Network (ANN) analysis was carried out to obtain the results of mathematical model. Experimental results indicated that ethanol blends yield higher torque than unleaded gasoline at retarded ignition timing. The maximum torque was obtained at 0.9 RAFR for all test fuels for compression ratios of 8:1 and 10:1. The results of mathematical model and experimentation were found to be within acceptable uncertainties. Ethanol – gasoline blends E0, E25, E50, E75 and E100 were tested by Celik [19] in a small gasoline engine. Tests were conducted in two stages. In the first stage tests were conducted at original 6:1 CR for 2000 engine rpm at WOT position. It was found in the test most suitable blend in terms of power and HC emission was E50. In the second stage tests were conducted with compression ratios 8:1 and 10:1. At CR 8:1 the engine produced knock with E0 and hence readings were not recorded. E50 enabled engine to run without any knock at high CR 10:1. The experimental results indicated that engine power increased by about 29% while running with E50 at high CR as compared to E0 fuel. The tests also indicated considerable reduction in HC, CO, NO_x and CO_2 with ethanol – gasoline blends. Experimental study on a four stroke SI engine by Najafi *et al.* [20] with ethanol-gasoline blends of 0%, 5%, 10%, 15% and 25% were also compared with the aid of ANN. The experimental results revealed marginal increase in BP, torque, BThE, VolE and decrease in BSFC with ethanol-gasoline blends. In exhaust CO and HC emission decreased where as NO_x and CO_2 were found to increase with ethanol-gasoline blends. The predictions of ANN analyses yielded correlation coefficient for model to be close to unity, while root mean square errors were very low. The analyses revealed a good correlation between ANN- results and experimental data.

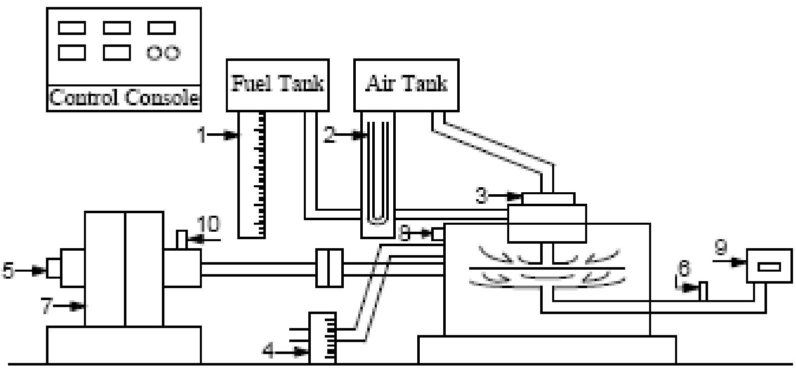
The literature review revealed that gasoline-ethanol blends in SI engine not only improve engine performance but also effectively lower emission as compared to conventional gasoline fuel. In this study P100-DNS blends were used to investigate effect of water content in DNS on exhaust emission.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The details of equipment, instrumentation, fuels used and methodology are discussed in following sub sections.

Engine and Equipment

Experimental set up consists of a four stroke, four cylinder carbureted SI engine coupled with an eddy current dynamometer. The specifications of engine, test rig and exhaust gas analyzer are given in Table 1, Table 2 and Table 3, respectively. Figure.1 shows a schematic diagram of the engine and instrumentation used for experimentation. Engine was loaded by dynamometer through a potentiometer provided on the panel. The dynamometer load was measured by a load cell. The water cooled piezo sensor was used to measure dynamic combustion pressure inside the combustion chamber. Fuel flow was measured by graduated burette and stop watch. The air flow was measured using air box method with differential pressure across the orifice was read using U-tube manometer. The exhaust gas under consideration was analysed by MRU Delta1600S to determine HC, CO, CO_2 and NO_x content.



1. Burette 2. Monometer 3. Carburettor 4. Rotameter 5. Speed Sensor 6. Thermocouple 7. Dynamometer 8. Pressure Sensor 9. Exhaust Gas Analyzer 10. Load Sensor

Fig. 1. Schematic diagram of experimental set up.

Table 1. Engine specifications.

Particulars	Specifications
Make	Premier(Fiat)
Number. of cylinders	4
BHP	39 @ 5000 rpm
Bore	68 mm
Stroke	75 mm
Cubic capacity	1089 cc
Compression ratio	7.8:1
Engine cooling	Water cooled

Table 2. Specifications of test rig.

Particulars	Specifications
Dynamometer	Eddy current
Model	E-50
Make	ATE
Load measurement	Load cell
Cylinder pressure measurement	Piezo sensor
Crank position measurement	Rotary encoder
Fuel flow measurement	Graduated burette
Air flow measurement	Air box method
Jacket water flow measurement	Rota meter
Interfacing	ADC/DAC

Table 3. Specifications of exhaust gas analyzer.

Particulars	Specifications
Make	MRU Delta 1600S
Storage temperature	-20^o C to 50^o C
Measure gases	**Units**
HC	ppm
CO	%
CO_2	%
NO_x	ppm

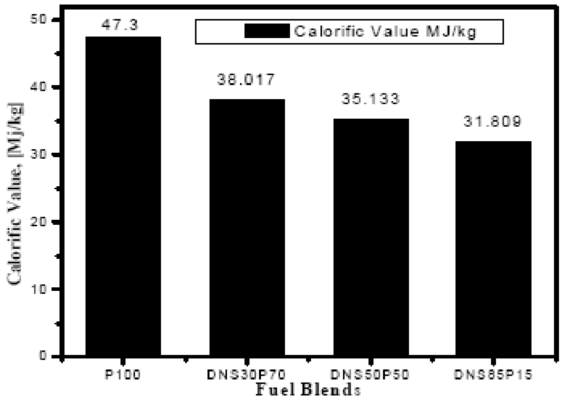


Fig. 2 Effect of addition of DNS on calorific value.

Table 4. Properties of ethanol and gasoline.

Property	Ethanol	Gasoline
Formula	C_2H_5OH	$C_{4\text{--}}H_{12}$
Molecular weight	46.07	100-105
Density kg/m^3	790	690-790
Stoichiometric A/F	9	14.7
Auto ignition temperature, ^{o}C	423	257
Flammability limit, Volume %		
Lower	4.3	1.4
Higher	19	7.6
Lower heating value, MJ/kg	27	44.5
Higher heating value MJ/kg	29.7	47.3
Heat of vaporization, KJ/kg	840	305
Octane number		
Research	108.6	88-100
Motor	89.7	80-90

Fuels

Locally available P100 was the base fuel. The DNS of over proof (O.P.) 63.7 was procured from Samsons Distilleries Pvt. Ltd., Karnataka, India and used in preparing blends. P100 was blended with DNS to prepare three test blends DNS30P70, DNS50P50 and DNS85P15. Table 4 gives properties of gasoline and ethanol.

Experimental Procedure

Tests were performed at engines speeds of 2500, 3000, 3500, 4000 and 4500 rpm, for 50% throttle position maintained throughout the experimentation. The tests were carried out starting with 2500 rpm as the sensors failed to respond and log the data at lower speeds. Being open loop engine test set up it was not possible to exactly maintain the speed for all trials and a variation of ±2% in speed was unavoidable. The observation for each blend with necessary retarding of ignition timing in view of higher flame speed of DNS/ethanol was made to ensure the Maximum Brake Torque (MBT) position. The test fuels used were P100 and DNS blends. The experiments were conducted for each blend at different speeds as mentioned. In order to compensate leaning effect of DNS, modifications in fuel supply system and ignition system were made. The ignition system used was pulsar coil distributor-less ignition system. The observations for each blend were taken after at least ten minutes of operation as to attain steady state condition. The required speeds were obtained through dynamometer load arrangement. Care was exercised to ensure complete usage of previous blend before the next blend was tested.

For each blend, at least three set of readings were taken to obtain an average value. The parameters continuously monitored were load, engine speed, fuel consumption, manometer reading and exhaust constituents (HC, CO, NO_x and CO_2). The average value of each parameter at all speeds and for each blend was calculated and used for comparison.

Heating values of fuels/blends were estimated through standard methods and it was noticed that heating value of blends decrease with increase in DNS % in blends as shown in Figure. 2. Various performance parameters such as fuel consumption, air consumption torque, BP, brake mean effective pressure (BMEP), IMEP, BSFC, BThE, VolE and A/F were computed.

3. RESULTS AND DISCUSSION

Engine performance parameters and exhaust gas emission for each blend were plotted individually against speed.

***Stoichiometric* A/F**

It is noticed from Figure 3 that stoichiometric air fuel ratio $(A/F)_s$ decreases as DNS % in blend increases. This behavior is owing to the fact that DNS being an oxygenated fuel provides additional oxygen thereby decreasing in $(A/F)_s$ with increase in DNS % in blend.

Brake Specific Fuel Consumption

The effect of DNS addition on BSFC is depicted in Figure 4. The calorific value of DNS (30.93 MJ / kg) is less compared to that of gasoline (47.3 MJ / kg). The lower calorific value of DNS causes leaning effect in blends as compared to gasoline operation. In order to compensate leaning effect in blends, fuel consumption increases with increase in DNS %. The experimental results indicate 31.41% increase in BSFC for DNS85P15 as compared to base fuel P100.

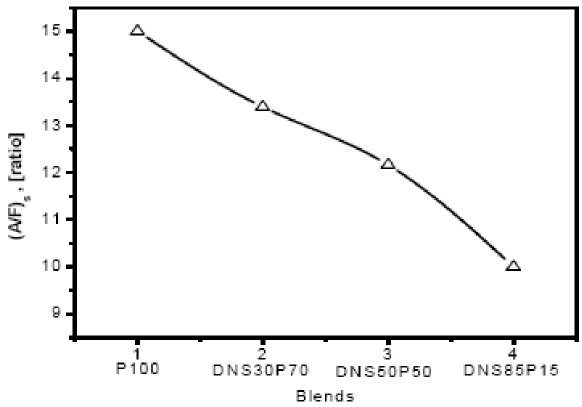


Fig. 3. Effect of DNS addition on $(A/F)_s$.

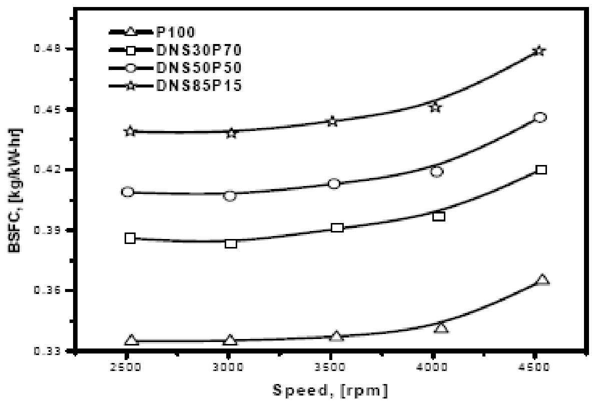


Fig. 4. Effect of BSFC with speed.

Volumetric Efficiency

The effect of DNS percentage in blend on volumetric efficiency of engine is shown in Figure 5. The figure indicates an increase in volumetric efficiency as DNS % in blend increases. Volumetric efficiency depends upon actual intake air quantity which is governed by operating temperature inside engine cylinder. The latent heat of vaporization is higher for DNS in comparison to gasoline which leads to considerable cooling of intake manifold and engine cylinder when compared to gasoline operation. This results in higher volumetric efficiency for DNS blends due to better charge density and more air induction for operation with blends. The volumetric efficiency for all blends along with gasoline operation is found to decrease with increase in engine speed due to increased operating temperature at higher speed of operation. The results for DNS85P15 operation indicates 8.71% rise in VolE as compared to P100 operation.

Torque and Brake Power

The engine performance indicators i.e. torque and brake powers for different DNS-gasoline blends are represented in Figure 6 and Figure 7. HHV of DNS85P15 (31.809 MJ / kg) is less compared to that of gasoline (47.3 MJ / kg). The relatively lower calorific value of DNS85P15 as compared with gasoline causes leaning effect in blends. In order to compensate for this leaning effect in blends, fuel consumption proportionately increases with DNS % in blend. The experimental results indicate 31.41% increase in BSFC for DNS85P15 as compared to base fuel P100. Higher HHV of gasoline by 32.75% compared to DNS leads to an increase in BSFC by 31.41% for DNS85P15 operation. This clarifies the quantitative balancing of fuels with respect to their HHVs. Ethanol in comparison to P100 has higher flame speed as indicated in [12], leaner flammability limits and high octane rating which ensure better combustion hence increased torque and brake power. Therefore DNS85P15 blend on qualitative basis also favors a higher BP output compared to P100 operation. It is quite obvious that, for all tested blends BP increases with engine speed.

The results indicate an increase of 13.11% and 12.46 % in torque and BP respectively for DNS85P15 as compared P100.

Brake Thermal Efficiency

Variation of brake thermal efficiency with engine speed for different percentage of DNS in blends is depicted in Figure 8. The engine behavior with increase in DNS % in blends is attributed to higher flame speed and leaner flammability of the DNS as compared to gasoline which leads to better combustion and higher brake thermal efficiency. The increase in fuel consumption to compensate for lower calorific value of blends at speeds beyond 2500 rpm is responsible for decrease in brake thermal efficiency. Engine operation from 2500 - 3000 rpm brake thermal efficiency increases, due to increase in volumetric efficiency as indicated in Figure 5 at 3000 rpm. The experimental result indicates an increase in BThE by 13.16 % for DNS85P15 in comparison to P100. BThE was calculated using Equation 1

$$\text{BThE} = \frac{\text{BrakePower(kW)}}{\text{Fuelconsumption (kg/sec)} \times \text{HHV of fuel (kJ/kg)}} \times 100 \quad \% \qquad (1)$$

Emissions

The effect of fuel blends on exhaust emission is discussed in this section and graphs are plotted for individual pollutants as a function of engine speed.

Carbon Dioxide

The effect of DNS addition in blends on CO_2 emission for different operating speeds is indicated in Figure 9. It is evident that CO_2 emission decrease as DNS % increases in blends; however decrease in CO_2 emission is much less when compared to other emissions. DNS as bio fuel, has good potential for lowering CO_2 emissions from well to tank. The reduction is due to ethanol which has high H/C ratio (3, against 1.8 for typical gasoline). CO_2 emission for DNS85P15 indicates decrease of 14.36% as compared to P100. The results obtained are in agreement with results of [13] and [19].

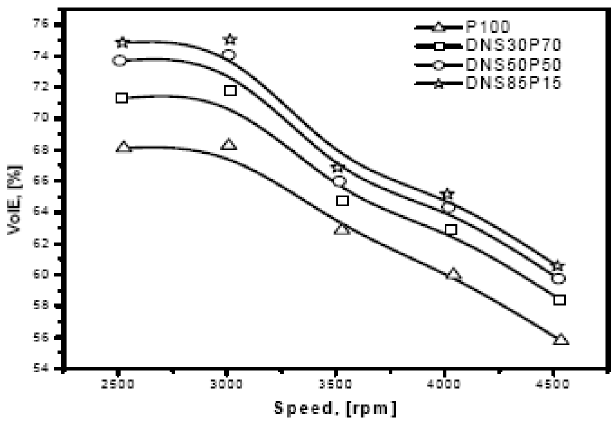


Fig. 5. Effect of VolE with speed.

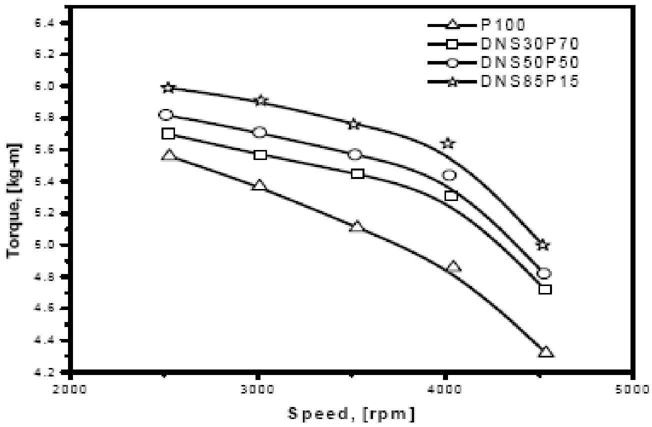


Fig. 6. Effect of torque with speed.

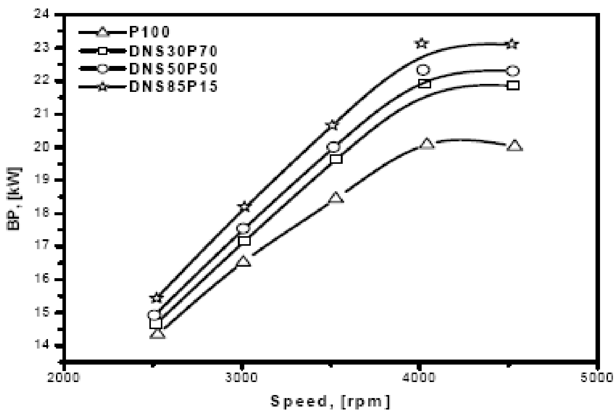


Fig. 7. Effect of BP with speed.

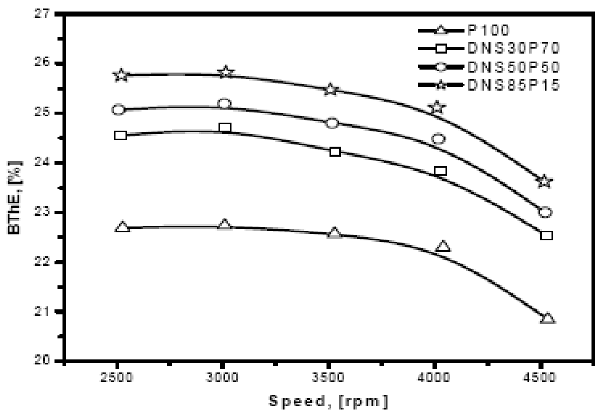


Fig. 8. Effect of BThE with speed.

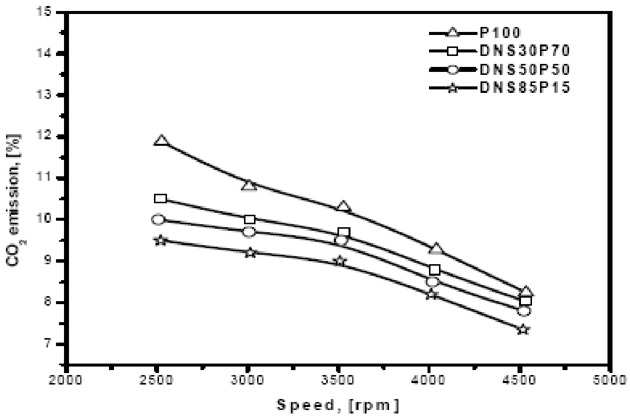


Fig. 9. Effect of CO_2 emission with speed.

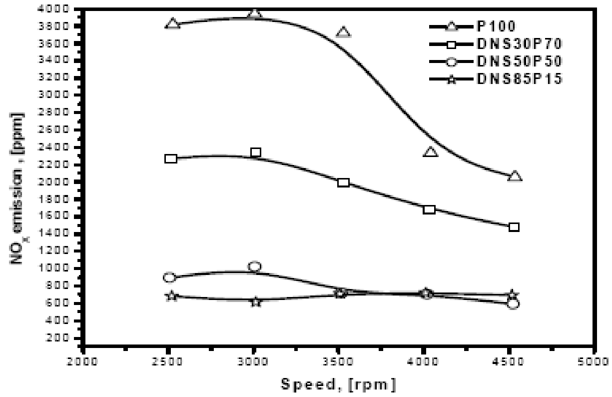


Fig. 10. Effect of NO_x emission with speed.

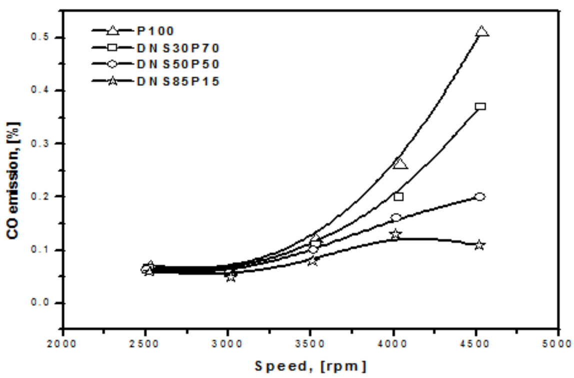


Fig. 11. Effect of CO emission with speed.

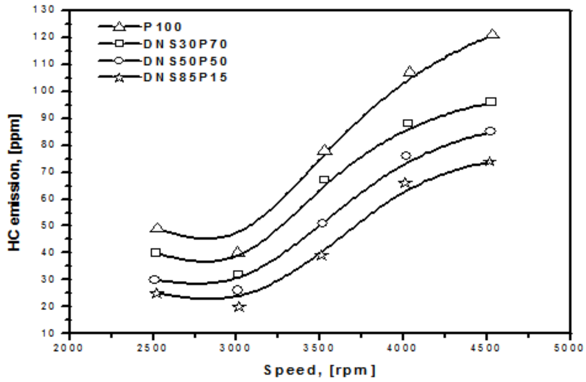


Fig. 12. Effect of HC emission with speed.

Oxides of Nitrogen

Effect of DNS addition in blends on NO_x emission is shown in Figure 10. It was noticeable that increase in DNS % in blends decreases NO_x emission. The water present in DNS blends during combustion keeps in-cylinder temperature lower leading to decrease in thermal NO_x formation. The experimental result is in agreement with observations of Oldberding *et al.* [7]. Observed value of NO_x for DNS85P15 shows dramatic reduction up to 78.50% as compared to P100 operation.

Carbon Monoxide

Effect of DNS percentage in blends on CO emission for different speeds is shown in Figure 11. Lean DNS-gasoline blends produce less CO emission due to presence of excess air. The water present in DNS blends by water-gas shift mechanism assists combustion process to reduce CO emissions. The CO emission reduces by 57.84% with DNS85P15 as compared to P100 operation. The results are in agreement with Oldberding *et al.* [7].

Hydrocarbons

The quantity of hydrocarbon emission in engine exhaust indicates the quality of combustion. The HC emission depends on combustion chamber design, engine operation and properties of fuel. In this study DNS has higher flame speed and better octane rating, which leads to better combustion and hence reduced HC emission. Figure 12 indicates effect of DNS addition on HC emission. HC emission was reduced by 43.29% with DNS85P15 as compared to P100.

4. SUMMARY AND CONCLUSION

The proven finding in this experiment was the inability of conventional ignition system to burn the higher proportions of DNS-gasoline blends; hence a more intense ignition system was inevitable. It is appreciably noticed that the thermal efficiency increases as the percentage of DNS increases in the blends. It is possible to further improve thermal efficiency by increasing compression ratio of engine in line with the high knock resistance of DNS.

The study attempts to reduce pollutant formation inside the combustion chamber instead of expensive post combustion treatment systems.

Experimentation on blends of both lower and higher proportions of DNS gives clear understanding of presence of DNS during combustion process influences power and exhaust emissions. The following conclusions were made in the study.

1. DNS as additive to unleaded gasoline improves engine performance and reduces exhaust emissions.
2. DNS85P15 fuel results in an increase of brake power, thermal efficiency, volumetric efficiency and specific fuel consumption by 12.46%, 13.16%, 8.71%, and 31.41%, respectively when compared to P100 operation.

3. DNS85P15 blend leads to significant reduction in exhaust emissions by 14.36%, 78.50%, 57.84%, and 43.29% of CO_2, NO_x, CO and HC, respectively when compared to P100 operation.
4. DNS85P15 blend produced better results in engine performance and reduced exhaust emissions amongst all tested blends.

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