Nitrogen enriched air for Nox reduction in Diesel engine

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Abstract: This paper analyzes the impact of nitrogen enriched air on emissions, in cylinder pressure, heat released during the working cycle and fuel consumption of a diesel engine. The experiment was performed on a naturally aspirated single cylinder diesel engine by increasing the nitrogen concentration supplied through a cylinder and NOx, CO, THC emissions were all measured with the help of a five gas analyzer. It was observed that enriching the inlet air with nitrogen decreases the NOx concentration considerably with a penalty on hydrocarbon emissions and thus the fuel conversion efficiency.

1. Introduction
Diesel and gasoline engines are a major source of modern day pollution. The exhaust gases from vehicles are hazardous to the environment as well as human beings. The combination of HC and NOx in the presence of sunlight and certain atmospheric conditions also produce photochemical smog. Deplete discharges comprising of oxides of nitrogen (NOx) from inward ignition motors depict a genuine issue. Despite the fact that the issue exists for both petrol and diesel engines, the issue is more serious for the diesel engine. In diesel engines the exhaust concentrations of NOx are considerably more than that in SI engines due to lean combustion. NOx emissions depends firmly on flame temperature, and flame temperature is subordinate upon the piece of the fuel and the admission air.

A large portion of these poisonous gases begin from different imperfect methodologies amid burning, for example, incomplete ignition of fuel, high pressure and temperature ignition, greasing up oil and oil added substances and in addition burning of non-hydrocarbon parts of diesel fuel, for example, sulfur mixes and fuel added substances. Regular exhaust emissions incorporate unburned hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx) or particulate matter (PM) Nitrogen oxides (NOx) are produced by the chemical reaction between nitrogen and oxygen in the combustion chamber under the high pressure and temperature conditions.

The major composition in the NOx exhaust is that of nitric oxide (NO) and a little division of nitrogen dioxide (NO2). The fuel is injected into the cylinder just before combustion starts, so throughout most of the critical parts of the cycle the fuel distribution is non-uniform. The pollutant formation process is strongly dependent on the fuel distribution and how that distribution changes with time due to mixing. Nitric oxide forms in the high temperature burnt gas regions. The critical time period is when the burned gas temperatures are at a maximum i.e. between the start of combustion and shortly after the occurrence of the peak cylinder pressure.

Mixture which burns early in the combustion process is especially important since it is compressed to a higher temperature, increasing the NO formation rate, as the combustion proceeds and cylinder pressure increases. Stringent emissions norms have been enforced by the government to restrict the emissions. Various strategies have been implemented over the years to reduce NOx emissions.

The possibility of various powertrains together with renewable vitality sources, to decrease discharges from vehicles have been broadly utilized. Enormous amount of research has been carried out on renewable energy resources such as LPG, Biodiesel etc.
2. Literature review
An exhaustive study on the nitrogen enrichment was carried out to better understand its impact on the diesel engine emissions and performance. Researchers used different techniques to reduce emissions and improve performance of a diesel engine.

Exhaust gas recirculation wherein a part of exhaust gas is recirculated into the cylinder intake charge reduces the peak cycle temperature as the inert gas acts as a heat sink [1]. There is also a reduction in the percentage of the combustion chamber oxygen content. This decreases the NOx emissions from the exhaust. Although EGR has been successfully implemented in modern day vehicles it has certain drawbacks. The NOx formation varies with the flow rate of the exhaust gases and hence the speed of the engine[2]. It also depends on the gas temperature and water content in the gases. Power and economy are significantly affected by the EGR. Smoke and particulate matter emissions are increased. Oil contamination and wear of the combustion chamber takes place due to the soot particle which are recirculated under high pressure thus engine lifespan is drastically affected [3].

Pertaining to the undesirable characteristics of EGR another way of reducing NOx is enriching the inlet with nitrogen gas [4]. As the NOx development essentially relies upon the rise in cylinder temperature and the habitation time of combustion, inclusion of nitrogen brings down peak ignition temperature with the included nitrogen contributing towards decreasing NOx instead of partaking in the ignition process. Nitrogen enhanced air effectively decreases NOx emissions without any unfavorable consequences on the engine lifespan [5].

Numerous researchers [6-10] have utilized nitrogen-enriched air to diminish NOx emissions in the diesel engine. These engine tests were led by utilizing bottled nitrogen, essentially to recreate the impacts of EGR. The flame temperature and oxygen concentration influence the NOx emissions which will be affected by nitrogen-enriched air.

Enhancing nitrogen content increases the heat capacity of the air mixture in the combustion chamber, which thus, decreases the in cylinder temperature of the combustion chamber [11]. The decreasing temperature due to mixing of high temperature gas with nitrogen gas thus freezes the NO chemistry. The impact of air oxygen content focus on the adiabatic flame temperature was analyzed by Olikara and Borman.

The adiabatic fire temperature diminishes with abatement in admitted oxygen levels at any air-fuel ratio. At the point when the oxygen content decreases from 21% to 17%, there is a diminishment in the stoichiometric fire temperature of around 250ºK, which aids in reducing the NOx emissions. This study analyzes the impact of admission of excess nitrogen on emissions, in cylinder pressure, heat released and fuel consumption. Bottled nitrogen is admitted into the engine, which displaces equal amount of oxygen.

3. Experimental setup
Tests were carried out on a Kirloskar diesel engine. The schematic diagram of the test set up is illustrated in figure 1. The engine is coupled to an eddy current dynamometer for varying the load on the engine by controlling the current supplied to the dynamometer.

Horiba exhaust gas analyzer model MEXA-584L was used to measure the THC, CO, NOx emissions. CO was measured using Non Dispersive Infrared (NDIR) method and chemiluminenscence principle was used to measure NOx. The exhaust gas was supplied to the Horiba analyzer after condensation in chilled thermally insulated container. Thermocouple sensor and display unit was used to measure the exhaust gas temperature.

AVL data acquisition system with the Indicom Mobile software user interface was connected to engine via various sensors for data measurement. Hall Effect rotary encoder (Encoders India make) was connected to the camshaft and proximity sensor to measure the TDC location was mounted near the flywheel. Piezo resistive pressure transducer (kistler make) was mounted in the combustion chamber and the signal was amplified using charge amplifier to calculate the Cylinder Pressure per degree Crankangle, Heat released per degree crank angle and MEP occurring during a cycle. Averaged
results for 50 cycles were obtained via Indicom mobile software. The engine specifications are also mentioned in table 1.

![Schematic diagram of the experimental setup](image)

Figure 1. Schematic diagram of the experimental setup

| Engine Characteristics | Specification |
|------------------------|---------------|
| **Engine model and type** | Kirloskar make single cylinder 4 stroke diesel engine |
| **Cooling** | Naturally aspirated |
| **Speed** | Constant |
| **Rated power** | 4.4 KW at 1500 rpm |
| **Bore** | 87.5mm |
| **Stroke** | 110mm |
| **Compression ratio** | 17.5 |

4. Methodology

Bottled nitrogen is introduced in the combustion chamber with the help of flow regulator attached to the nitrogen cylinder. Oxygen sensor is mounted onto the inlet supply line to monitor the percentage of oxygen. As the nitrogen is supplied to the engine it displaces equal amount of oxygen gas thus reducing the volume content of the oxygen and air becomes rich with nitrogen. The percent decrease in the oxygen concentration of air is analogous to the percent increase in the nitrogen gas. Air is enriched with nitrogen in 3 steps from 79% to 80.5%. Table 2 illustrates the oxygen concentration in the intake air measured with the help of oxygen sensor and the corresponding nitrogen gas concentration.
Table 2. Percentage of oxygen and nitrogen supplied

| Oxygen % | Nitrogen % |
|----------|------------|
| 21       | 79         |
| 20.5     | 79.5       |
| 20       | 80         |
| 19.5     | 80.5       |

5. Results and Discussion

Following are the results obtained from the experiments along with the discussion on the various trends observed is presented.

5.1. Load vs Carbon Dioxide

Figure 2 shows the CO$_2$ against Load when Nitrogen enriched air with various percentage of nitrogen is introduced in to the engine. CO$_2$ emission is almost constant as Carbon/ Hydrogen ration of fuel is not affected by the Nitrogen enriched air.

5.2. Load vs Carbon Mono-oxide

Figure 3 shows CO emissions for different Load when Nitrogen enriched air is admitted in to the diesel engine. As the nitrogen percentage in inlet air is increased, it is observed that variation in CO percentage of exhaust gas volume is very less and can be considered as constant.
5.3 Load vs Hydro carbon
Figure 4 shows the HC emissions against load with increasing concentration of Nitrogen in inlet air. It is observed that HC emissions are drastically increased, when Nitrogen concentration is increased from 79 % to 79.5 %. This increase in HC emission is due to reduction of Oxygen percentage in inlet air. When the percentage of Nitrogen is increased from 79.5 % to 80.5 %, there is slight increase in HC emissions. Increase in HC emissions with Nitrogen Enriched Air indicates that less quantity of fuel was burned during combustion.

5.4 Load vs Nitrogen Oxide
Figure 5 shows the Load vs Oxides of Nitrogen. When the Nitrogen rich air is admitted in to the cylinder, NOx is drastically reduced up to the 80 % of N2 in air. This is due to less Oxygen avalibility for combustion, which in turn reduces the heat release rate, hence maximum temperature during cycle. Reduced maximum temperature resist the dissociation during cycle and Reduced values of NOx were observed.
5.5 Load vs Oxygen

Figure 6 Shows trade off between Load and percentage of Oxygen in exhaust gas. Percentage of Oxygen in exhaust gas is observed as reducing with increasing with not only Load but also percentage enrichment of Nitrogen gas. With load it is reducing because as the load is increased more fuel is admitted in to the cylinder in order to maintain the speed constant, more Oxygen content from inlet air is utilized to burn the fuel during combustion. It is very obvious that Oxygen content in exhaust is reduced with N2 enrichment at inlet air which in turn reduces the Oxygen percentage at inlet and during whole cycle.

![Graph](Image1.png)

Figure 6. Load vs O2% in exhaust gas

5.6 Crank angle vs in-cylinder Pressure

Figure 7 depicts the Crank angle against cylinder pressure for various percentage of N2 enrichment. Pressure almost maintained constant but the maximum pressur values are delayed slightly with increasing with increasing percentage of N2 in inlet air. It is explained as , when the N2 is added in the inlet air, oxygen percentage in the air reduces which slowed down the combustion rate, took more time for releasing heat available in the fuel.

![Graph](Image2.png)

Figure 7. Crank Angle vs Pressure at 60%
5.7 Crank Angle vs Heat release
Figure 8 shows variation of the heat release rate for 60 % of load with crank angle. Heat release curve is obtained for different percentage of N₂ in the inlet air. As the increment in N₂ percent in the inlet air is very less, there is no significant change in the trade off between crank angle and Heat release with N₂ enrichment. From the curve it is evident that maximum heat released is shifting closer to the TDC due to slower combustion rate obtained because of less availability of Oxygen.

![Crank Angle Vs Heat Release at 60 % Load](image1)

Figure 8. Variation of Heat Release at 60% load vs Crank Angle

5.8 Load vs Indicated thermal efficiency
Figure 9 depicts the Load versus Indicated thermal efficiency with Nitrogen enrichment. For the percentage 79.5 % to 80 % N₂ in the inlet air there was no much change was observed. This is due to the fact the there is very less N₂ enrichment which kept the heat release rate almost constant. But for the 80.5 % N₂ enrichment reduced indicated efficincy was observed. Hence more that 80 % N₂ enrichment is limited by the Indicated thermal efficicncy.

![Load vs Indicated Thermal Efficiency](image2)

Figure 9. Load vs Indicated Thermal Efficiency
5.9 Load vs BSFC
Figure 10 shows the variation of load vs Bsfc, and it indicates that Bsfc nearly constant for various N2 enrichment because diesel engines are always operated at lean condition which ensures the availability of Oxygen for small increment in N2 in inlet air.

![Figure 10. Load vs BSFC](image)

6. Conclusion
Following are the conclusion drawn from the research study carried out on the diesel engine to study its impact on the nitrogen enrichment.

- Nitrogen increase from 79 % N2 to 79.5 % N2 HC emissions increase drastically indicates more fuel is required for constant Break power. 79.5 % N2 to 80.5 % N2 increase rate of HC emission is less indicating slight increase in mass flow rate of fuel is required. Hence the N2 enrichment slightly reduces the fuel economy.

- Nitrogen increase from the 79 % N2 to 80.5 % N2, Nitrogen oxide keep on reducing but maximum value of N2 enrichment is limited by the Indicated thermal efficiency. Optimum enrichment in order to reduce NOx should have 80 % of N2 in the inlet air which reduces NOx without much increase in the break specific fuel consumption.

- For 80 percentage of N2 enrichment in the inlet air, Indicated thermal efficiency is almost constant

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