Investigation of Oxygen Enriched Air Intake on Diesel Engine Exhaust Emissions

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Abstract: One of the methods to reduce the emissions in a diesel engine is by oxygen introduction into the combustion chamber which can be done by supplying the oxygen into the inlet manifold during suction stroke. Oxygen affects different parameters such as brake thermal efficiency, fuel consumption, NOx and smoke at different load conditions. Load test was conducted for various concentrations of oxygen (21 to 27 percent) in terms of 2%. It is found that oxygen enrichment leads to better combustion which in turn results in less fuel consumption and an increase in brake thermal efficiency. It was found that about 25% oxygen enrichment in the inlet air results in the optimum performance and emission characteristics. The result shows that varying oxygen enrichment in the inlet air increases brake thermal efficiency and subsequently decreases brake specific fuel consumption. It was also found that an oxide of nitrogen (NOx) increases exponentially whereas smoke intensity falls bellow the normal level.

Keywords: Diesel Engine, Efficiency, Emission, Fuel Combustion, Oxygen Enrichment

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1 INTRODUCTION

In most combustion processes, various kinds of hydrocarbon fuels are used. Regarding fossil fuel combustion, due to increasing concerns over environmental pollutants such as soot particulates, carbon monoxide, unburned hydrocarbon, nitrogen oxides and sulfur dioxide, development of emission reduction methods has become an imminent issue for practical application to numerous combustion devices. Reduction of engine emissions is a major research aspect in engine development with the increasing concern on environmental protection and the stringent exhaust gas regulations.

It is difficult to reduce all emissions simultaneously in normal Diesel engines. Many in-cylinder and exhaust post-treatment techniques are currently being investigated to reduce NOx and smoke emissions to the acceptable levels. Altering the composition of air provides automotive engineers to solve difficult environmental problems.

One prospective method to reduce Diesel engine emissions is to use oxygenated alternative fuels or to add the oxygenated fuels in the Diesel fuel to provide more oxygen during combustion. Oxygenated alternative fuels like biodiesel, ethanol, dimethyl-ether, methanol and Fischer-Tropsch diesel fuel and oxygenated fuel additives have been utilized for reduction of Diesel engine emissions[1]-[18].

Another technology for emission reduction from diesel engine is oxygen enrichment of intake air. Several scientists reported that low emission and high energy efficiency could be achieved if oxygen enriched air was used in order to induce the complete combustion [19]-[26]. The oxygen enriched air can be obtained by using the oxygen membrane through which oxygen can permeate more than nitrogen. There have been several studies on the application of gas membranes to the internal engine in order to figure out the effects of oxygen enriched air on the emission gases [19], [20].

Watson, et al conducted experiments with oxygen-enriched air (up to 30% O_2 by volume). They achieved about 80% reduction in smoke at full load and 5% to 12% increase of thermal efficiency and also a decrease of CO and HC emissions. However, NOx increased due to the increase of oxygen concentration and cycle temperatures [21].

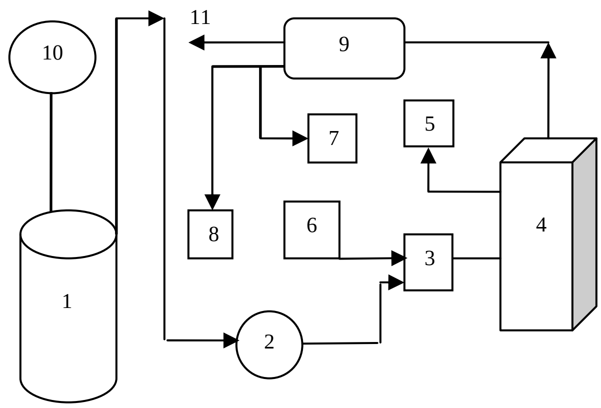
Poola, et al. conducted experiments with oxygen enriched air in a SI engine to mainly reduce HC and CO emissions. It had a great advantage in the period where the catalytic converter temperature was below light off level. They achieved about 60% to 70% reduction in HC and CO emission levels with an increase of 23% of oxygen by volume [22].

Donahue and Foster concluded that oxygen enrichment increases NOx through increased temperatures and oxygen concentration. It decreases particulates through reduced fuel pyrolysis and increased soot oxidation. Increased oxygen concentration had a thermal and dilution effect on NOx emissions and it was concluded that optimising the injection timing could have further improvements [23].

In this study, the effects of enriched oxygen on the emission gas of a diesel engine were investigated. The diesel engine used in this study was a single-cylinder one.

2 EXPERIMANTAL PROCEDURE

Test engine used in the experiments is a single cylinder four-stroke, naturally aspirated, constant speed compression ignition engine, coupled to a three-phase alternator for its loading. The experimental set-up is shown in block diagram in Figure 1. Engine was tested at a rated speed of 1500 rpm. The exhaust gas was sent to the smoke meter and gas analyzer to measure smoke density, CO, NO_X, etc. The readings taken during each set of experiments was used for the calculation of brake specific consumption, thermal efficiency, and other engine characteristics. Every experiment was repeated 3 times and readings of experiments for every parameter were almost the same.



(1) Oxygen cylinder; (2) Gas flow meter; (3) Mixing chamber; (4) engine; (5) Exhaust gas thermometer; (6) Orifice meter; (7) NOx meter; (8) Smoke meter; (9) Exhaust; (10) Pressure gauge; and (11) to atmosphere

Fig. 1 Experimental set-up

When the test engine reached stable condition and preparations and settings for the measurements were finished the experiments started. The type of experiment is a study state engine test. Application of loads included five levels: 20%, 40%, 60%, 80% and 100% loads respectively. In each load level, measurements of different parameters were carried out.

The general specifications of the engine are given in Table 1. A temperature gauge was connected to the exhaust manifold of the engine to measure the exhaust gas temperature.

In the present study, the effects of oxygen enrichment in the intake air content in diesel combustion and emissions were studied separately at different loads in a DI diesel engine at a constant speed of 1500 rpm. The oxygen concentration of the intake air was increased by injecting pure oxygen from a compressed cylinder to the mixing chamber. To ensure effective oxygen enrichment, the pure oxygen was injected directly through mixing chamber in its inlet and the intake air oxygen concentration was measured properly using gas flow meter.

The aim was to see if a suitable oxygen concentration could be suggested to improve the performance of the engine and reduce its emissions. The emission changes with various oxygen concentrations (21-27%) were measured. Higher oxygen enrichment levels needs special engine modifications because of the higher output temperature which is expected to be produced. Properties and characteristics of diesel fuel that was used in the experiments are shown in Table 2.

Table 1 Transitions selected for thermometry

Engine Type	four-stroke cycle, naturally aspirated, compressed ignition diesel engine
Number of cylinders	single
Bore, mm	85
Stroke, mm	107
Cubic capacity, cc	607
Compression ratio	17
Speed, rpm	1500
Power, kW	4/5
BHP	6

Table 2 Transitions selected for thermometry

Fuel Property	Diesel oil
Density at 15°C(kg/m3)	840
HHV (MJ/kg)	44.65MJ/kg
LHV (MJ/kg)	42.15MJ/kg
Viscosity(mm2/s)	3.647
Compression ratio	17
Flash Point(°C)	64
Pour Point(°C)	-6
C (wt%)	85.0
H (wt%)	13.0
Sulfur content (wt%)	0.85
N (wt%)	0.0
Water content (mg/kg)	97

3 THEORETICAL INVESTIGATION

Chemical formulation of the fuel was determined approximately as $C_{13.2}H_{23.5}$. In equation (1) the chemical reaction of the fuel with atmospheric air is expressed as:

$$C_{13.2}H_{23.5} + a_{th}(0.21O_2 + 0.79N_2) \rightarrow 13.2CO_2 + 11.75H_2O + 0.79a_{th}N_2 \quad (1)$$

By increasing oxygen concentration, equation (1) can be expressed as:

$$C_{13.2}H_{23.5} + a_{th}(eO_2 + (1-e)N_2) \rightarrow 13.2CO_2 + 11.75H_2O + (1-e)a_{th}N_2 \quad (2)$$

where “e” is oxygen fraction in intake air. After determining the enthalpy of fuel formation, the theoretical heat transfer from combustion at different oxygen concentrations in intake air can be calculated. When oxygen enriched air is used the heat that is released is determined as q_{enrich} and ratio of q/ q_{enrich} is determined as “y “. The calculation results of heat transfer for different oxygen concentration levels are summarized in Table 3.

Table 3 Results of theoretical calculation

e	a_{th}	q (kJ/kmol)	q (kJ/kg)	y
0.21	90.83	-3911753.2	-21505	1
0.23	82.93	-4187733.6	-23022.2	0.934
0.25	76.30	-441919397.7	-24295.7	0.885
0.27	70.65	-4616803.6	-25381	0.847

4 RESULTS AND DISCUSSION

By increasing oxygen concentration in intake air the heat that is released from combustion reaction, is also increased. By assuming heat transfer from combustion, the same for all oxygen concentration levels, the rate of fuel consumption is reduced along with increasing oxygen concentration in intake air. We can determine the percent of fuel consumption with respect to the initial state in which pure air with 21% oxygen by volume had been used. By increasing the amount of oxygen from 21% to 27%, variation of fuel consumption rate in different loads can be seen in Figure 2. As depicted in Table 4, the practical fuel consumption achieved for different oxygen concentration levels is compared to theoretical calculations.

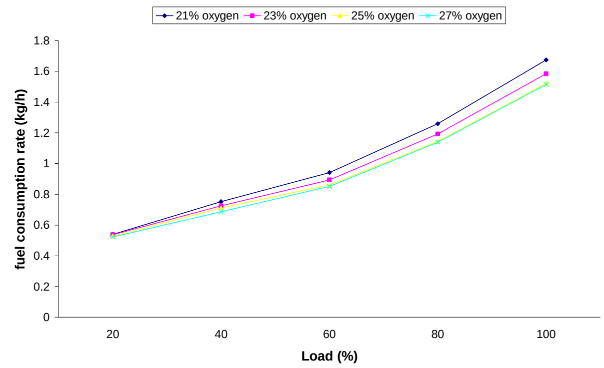


Fig. 2 Fuel consumption rate with load

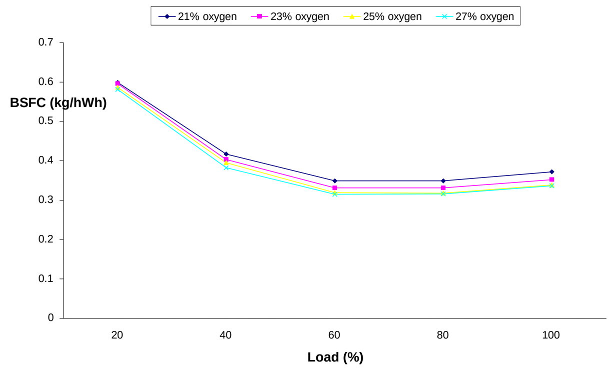


Fig. 3 Variation of BSFC with oxygen enrichment and load

Table 4 Fuel consumption reduction ratio

Oxygen (%) \ Load (%)	20	40	60	80	100	theory
21	0	0	0	0	0	0
23	0.37	3.6	5.1	5.3	5.4	6.6
25	2	5.3	8.6	9	9.1	11.5
27	3	8.6	9.5	9.5	9.6	15.3

It can be seen that by increasing the load, experimental results converge to theoretical calculations. In other words, oxygen enrichment in intake air leads to more efficient fuel consumption reduction in higher loads. As shown in Figure 2, by increasing the load, fuel consumption rate also increases and reduction of fuel consumption is more important.

The results presented here are with respect to the oxygen concentration in the inlet air varying from 21% to 27% by volume. The effects of various intake oxygen concentration as a function of engine load on performance and emission characteristics were shown in Figures 3 to 6.

Figure 3 shows the variation of brake specific fuel consumption (BSFC) versus load for different oxygen concentrations in intake air. As the load increases, BSFC decreases for all concentrations. At higher loads, BSFC tends to increase a little; it may be the outcome of increasing friction power in higher loads. Oxygen enrichment decreases the BSFC at all loads. The decrease in BSFC is due to increase in oxygen content in the intake air, which burns additional fuel, resulting in the decrease of the BSFC. It is observed that under full load condition with 25% oxygen enrichment, brake specific fuel consumption was decreased from 0.372kg/kWh to 0.336kg/ kWh.

BSFC is related with brake thermal efficiency. By increasing oxygen concentration, brake specific fuel consumption decreases and the brake thermal efficiency is increased.

Figure 4 shows variation of brake thermal efficiency (BTE) versus load under various oxygen concentration levels. Brake thermal efficiencies rise from lower to higher load levels. This is so, because work done at higher load levels produces higher power output and brake thermal efficiency. Therefore at 0 load level, there is no work done and no brake thermal efficiency. The brake thermal efficiency is lowest with 21% oxygen in intake air for all loads.

The thermal efficiency generally increases with an increasing amount of oxygen from 21%, 23%, and 25% by volume, but shows no increase for 27% oxygen enrichment above 50% load. The increase in oxygen from 25% to 27% does not have any effect on combustion. Peak brake thermal efficiency occurs at 25% oxygen concentration and is about 3% higher than the engine efficiency corresponding to 21% oxygen concentration.

Smoke contains solid carbon soot particles which are generated when the fuel has not enough oxygen for all the carbon to react with or in the fuel rich zone of combustion chamber during combustion process.

Figure 5 shows the variation of smoke density with load ranging from zero to full load for varying oxygen concentrations. Smoke density drastically decreases with increase in oxygen concentration at all loads due to better oxidation of soot. The enhanced oxygen flow rate improves the diffusion combustion process which results in less smoke. At full load, for 25% oxygen concentration, smoke density was reduced from 93% to 68% and it is further reduced to 54% at 27% oxygen concentration.

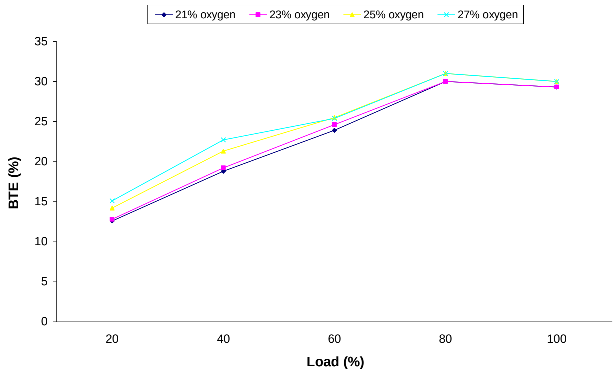


Fig. 4 Variation of Brake Thermal Efficiency with oxygen enrichment and load

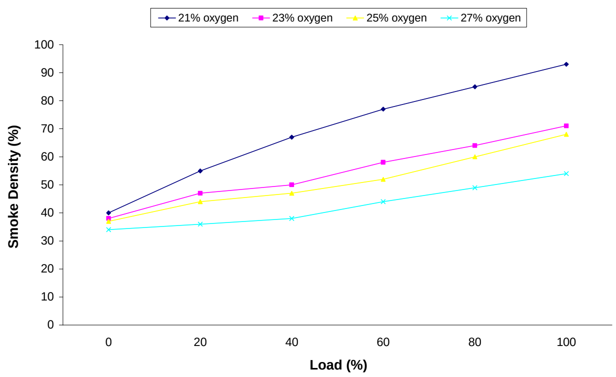


Fig. 5 Variation of Smoke Density with oxygen enrichment and load

The effect of intake air oxygen enrichment on NOx emission under load ranging from zero to full load is depicted in Figure 6.

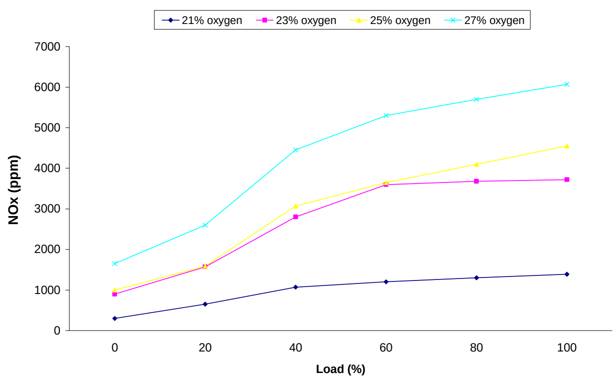


Fig. 6 Variation of NOx versus load for different oxygen enrichment levels

NOx emission significantly increases with increase in oxygen level in all loads. The tendency of increase in NOx is almost exponential with increasing oxygen. This is a result of the increased oxygen availability while the temperature is high. NOx emission rises from 1390 ppm for the base engine to 4550 ppm with 25% oxygen concentration level at full load. Additional supply of oxygen increases the NOx emission.

High oxygen concentration is one of the reasons of NOx increase when the oxygen enriched air is used. The number of oxygen molecules per cycle increased with the increase of oxygen concentration while the number of nitrogen molecules and combustion temperature did not change much. It can be concluded that the increase of NOx is caused mainly not by high temperature of the engine but by higher number of oxygen molecules per cycle. CO concentration in exhaust gases varied from 0.242% under 0% load to 1.518% under 100% load. By increasing oxygen concentration, CO concentration reduced 31%, 39% and 51% respectively for 23%, 25% and 27% oxygen by volume in intake air. Engine power and torque was observed to remain unaffected by intake air oxygen enrichment.

5 CONCLUSION

The use of oxygen enrichment on diesel engine under different loading conditions was studied to discuss various parameters like brake specific fuel consumption, brake thermal efficiency, smoke density, NOx and CO emissions. The main observations are:

1- Fuel consumption rate decreases, with increase of oxygen concentration level, heedless of the amount of load it has undergone. By increasing the load, rate of fuel consumption is gradually reduced until it approximates the theoretical calculated rate.

2- Brake specific fuel consumption is decreased by oxygen enrichment, at all loads.

3- Brake thermal efficiency increases at all loads till oxygen concentration level of 25%.

4- The higher the concentration of oxygen, the higher the reduction of smoke density and CO in exhaust gas.

5- NO_X emission increases with increasing amount of oxygen in the intake air ranging from no load to full load conditions. This is due to increase in oxygen concentration at high combustion temperature.

6- As oxygen concentration in the air intake is increased, maximum torque and power of the engine remains intact. In practice, while intake air's oxygen is being enriched, supplementary treatment for reducing NOx should also be carried out, or else the optimum oxygen concentration for each diesel engine should be found in order to reduce all emissions without substantial increase of NOx.

REFERENCES

[1] Arrègle, J., López, J. J., García, J. M., and Fenollosa, C., "Development of a zero-dimensional diesel combustion model. Part 1: analysis of the quasi-steady diffusion combustion phase", appl. thermal eng., Vol. 23, No. 11, 2003, pp. 1301–1317.

[2] Song, K. H., Nag, P., Litzinger, T. A. and Haworth, D. C., "Effects of oxygenated additives on aromatic species in fuel-rich, premixed ethane combustion: a model- ing study", combustion flame, Vol. 135, No. 3, 2003, pp. 341–349.

[3] Saito, M., Sato, M., Murata, H. and Sadakata, M., "Combustion rates of pulverized coal particles in high-temperature/high-oxygen concentration atmosphere", combustion flame, Vol. 87, No. 1, 1991, pp. 1–12.

[4] Singh, J., Mishra, T. N., Bhattacharya, T. K. and Singh, M. P., "Emission characteristics of methyl ester of rice bran oil as fuel in compression ignition engine", world academy of science, engineering and technology, 2007.

[5] Prashant, G., Soni, S. K., Kundu, K. and Srivastava, S., "Effect of blends of rubber seed oil on engine performance and emissions", 2008.

[6] Lei, J., Bi, Y. and Shen, L., "Performance and emission characteristics of diesel engine fueled with ethanol-diesel blends in different altitude regions", hindawi publishing corporation, 2011.

[7] Ciniviz, M., "Performance and energy balance of a low heat rejection diesel engine operatedted with diesel fuel and ethanol blend", transactions of the canadian society for mechanical engineering, Vol. 34, No. 1, 2010.

[8] Rakopoulos, C. D., Antonopoulos, K. A., Rakopoulos, D. C. and Hountalas, D. T., "Multi-zone modeling of combustion and emissions formation in DI diesel engine operating on ethanol diesel fuel blends", energy conversion and management, Vol. 49, No. 4, 2008, pp. 625–643.

[9] Shen, L. Z., Yan, W. S., Bi, Y. H. and Lei, J. L. "Performance comparison of ethanol/diesel blends mixed in different methods of diesel engine", Journal of Combustion Science and Technology, Vol. 13, No. 5, 2007, pp. 389–392.

[10] Fleisch, T. H., Basu, A., Gradassi, M. J. and Masin, J. G., "Dimethyl ether: a fuel for the 21st century", studies in surface science and catalysis, Vol. 107, 1997, pp. 117-125.

[11] Fleisch, T. H., Basu, A., Gradassi, M. J. and Masin, J. G., "Dimethyl ether: a fuel for the 21st century", studies in surface science and catalysis, Vol. 107, 1997, pp. 117-125.

[12] Semelsberger, T., Borup, R. and Greene, H., "Dimethyl ether (DME) as an alternative fuel", Journal of Power Sources, Vol. 156, 2006, pp.497–511.

[13] Bo, Z., Weibiao, Fu. and Jingsong, G., "Study of fuel consumption when introducing DME or ethanol into diesel engine" , Elsevier, fuel, Vol. 85, 2006, pp. 778–782.

[14] Zhao, X., Ren, M. and Liu, Zh., "Critical solubility of dimethyl ether (DME)+diesel fuel and dimethyl carbonate (DMC)+diesel fuel", fuel, Vol. 84, 2005, pp. 2380-2383.

[15] Haribabu, N., Appa Rao, B. V., Adinarayana, S., Sekhar, Y. M. C. and Rambabu , K., "Performance and emission studies on di-diesel engine fueled with pongamia methyl ester injection and methanol carburetion", Journal of Engineering Science and Technology, Vol. 5, No. 1 ,2010, pp. 30 – 40.

[16] Kumar, M. S., Ramesh, A. and Naglingam, B., "An experimental comparison of methods to use methanol and jatropha oil in a compression ignition engine", biomass and bioenergy, Vol. 25, No. 3, 2003, pp.309-318.

[17] Huang , Z. H., Ren, Y., Jiang, D. M., Liu, L. X., Zeng, K., Liu, B., and Wang, X. B., "Combustion and emission characteristics of a compression ignition engine fuelled with diesel–dimethoxy methane blends", energy conversion and management, Vol. 47 , 2006, pp.1402–1415.

[18] Nibin, T., Sathiyagnanam, A. P., Sivaprakasam, S. and Saravanan C. G., "Investigation on emission characteristics of a diesel engine using oxygenated fuel additive", 2005.

[19] Rigby, G. R. and Watson, H. C., "Application of membrane gas separation to oxygen enrichment of diesel engines", J. membr. sci., No. 87 ,1994, pp.159–169.

[20] Byuna, H., Honga, B. and Lee, B., "The effect of oxygen enriched air obtained by gas separation membranes from the emission gas of diesel engines", desalination, Vol. 193, 2006, pp. 73-81.

[21] Watson, H. C., et al., "A new look at oxygen enrichment in diesel engine", SAE paper, No. 900344.

[22] Poola, R. B., et al., "Utilizing intake air oxygen-enrichment technology to reduce cold-phase emissions", SAE paper, No. 952420.

[23] Donahue, R. J. and Foster, D. E., "Effect of oxygen enhancement on the emission from DI diesel via manipulation of fuel and combustion chamber gas composition", SAE paper, No. 2001-01-0512.

[24] Song, J., Zello, V. and Boehman, A. L., "Comparison of the impact of intake oxygen enrichment and fuel oxygenation on diesel particulate emissions", fuel chemistry division preprints, 2002.

[25] Anand, R. and Mahalakshmi, N. V., "The effects of oxygen enrichment with intake air in a direct injection diesel engine", IE(I) Journal-Mc, Vol. 90, 2010, pp. 44-47.

[26] Udayakumar, R. and Meher, A. K., "Use of oxygen enriched air in a direct Injection diesel engine", IE (I) Journal- Mc, Vol. 86, 2005, pp.156-159.