Engineering Science and Technology, an International Journal 19 (2016) 438–443

HOSTED BY

Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: http://www.elsevier.com/locate/jestch

Full Length Article

# Effects of oxygen enriched combustion on pollution and performance characteristics of a diesel engine

P. Baskar *, A. Senthilkumar

*Faculty of School of Mechanical and Building Sciences, VIT University, Vellore 632014, India*

A R T I C L E I N F O

*Article history:*
Received 19 June 2015
Received in revised form
12 August 2015
Accepted 31 August 2015
Available online 26 September 2015

*Keywords:*
Oxygen enrichment
Combustion
Performance
Emission
Diesel engine

A B S T R A C T

Oxygen enriched combustion is one of the attractive combustion technologies to control pollution and improve combustion in diesel engines. An experimental test was conducted on a single cylinder direct injection diesel engine to study the impact of oxygen enrichment on pollution and performance parameters by increasing the oxygen concentration of intake air from 21 to 27% by volume. The tests results show that the combustion process was improved as there is an increase in thermal efficiency of 4 to 8 percent and decrease in brake specific fuel consumption of 5 to 12 percent. There is also a substantial decrease in unburned hydro carbon, carbon mono-oxide and smoke density levels to the maximum of 40, 55 and 60 percent respectively. However, there is a considerable increase in nitrogen oxide emissions due to increased combustion temperature and extra oxygen available which needs to be addressed.



## 1. Introduction

Diesel engine manufacturers face a major challenge to meet the standards of stringent emissions of smoke, unburned hydrocarbon, carbon monoxide and oxides of nitrogen coupled with increasing the performance of the engine. Over the years, engineers have tried a number of different techniques to improve the combustion and reduce the pollution levels with considerable success rates. The imperatives for achieving the good thermodynamic performance in internal combustion engine are highlighted by Borman and Ragland [1] and Baukal [2]:

- Minimal energy consumption in the preparation of the fuel.
- A fuel of high mass specific energy that occupies minimal volume.
- A sufficiently high energy inhalation rate, with flows of fuel and oxygen that facilitate reaction.
- An operation cycle of the highest possible thermodynamic cycle efficiency.

Heywood J.B [3] in his text clearly indicated that, to ensure complete combustion even with latest technologies the engines must operate in excess air. That is, more air carrying 21% $O_2$ by volume is passed through the intake valve than the chemically required (stoichiometric) and this process ensures that nearly all fuel molecules receive required oxygen for complete combustion. Excess air speeds up the mixing of fuel with air and ensures complete combustion of fuel but at the same time excess air wastes heat energy by carrying it in the exhaust gases. If sufficient oxygen is not provided to the engine during combustion process, complete conversion of carbon and hydrogen is impossible to attain and that leads to particulates and carbon monoxide resulting in increased exhaust emissions.

A number of analytical and experimental studies [3–21] have demonstrated the benefits of using oxygen enriched combustion in diesel engines. The results of all these investigation show a considerable decrease in unburned hydrocarbon, carbon monoxide emissions and smoke while oxides of nitrogen emissions increased pro-rata with the oxygen added. Cole et al. [5] studied the effect of water injection in combustion chamber to reduce nitrogen oxide emission from oxygen enrichment and reported favorable results. Chin [6] has found in his investigation that increased oxygen level in the combustion chamber tends to reduce the energy required to burn combustible mixture. Enriching the intake air with oxygen led to a large decrease in ignition delay and reduced combustion noise. Increasing the oxygen content to a reacting fuel-oxidizer mixture leads to faster burn rates and the ability to burn more fuel at the same stochiometry (oxygen to fuel ratio). These effects also have the potential to increase the thermal efficiency and specific power output of the diesel engine. Increased oxygen level in the combustion chamber can be achieved either by mixing it in the intake air or by using oxygenated fuels. Both techniques almost have the same impact on the combustion as the results of Donahue and Foster [8] indicate. Lida et al. [10] reported a better combustion with increased oxygen resulting in reduced particulates from

* Corresponding author. Tel.: +91 9486114993; fax: +91 4162243092.
*E-mail address:* pbaskar@vit.ac.in (P. Baskar).
Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2015.08.011

the exhausts. One of the promising advantages of using oxygen enhanced combustion is that inferior quality fuels can be used in the engines without affecting overall performance of the engines as it was reported by Marr et al. [11]. Poola and Sekar [12] identified an operating regime in which both the particulates and nitrogen oxides can be reduced. They also observed a higher gross power, lower peak cylinder pressure and lower brake specific fuel consumption. Oxygen enhancement for intake air may be achieved by means of membrane technology or molecular sieve that can be incorporated in the intake air system through the air cleaner as investigated by Poola et al. [13]. One of the potential drawbacks of oxygen enrichment is increased oxides of nitrogen from the tailpipe; however, this can be controlled by emulsified diesel as the results of Sekar et al. [15] and Subramanian and Ramesh [17] reports shows. Song et al. [16] compared the combustion and emission characteristics of oxygenated fuel and raw oxygen added into the intake air and found that the combustion characteristics of hydrocarbon fuel enhanced by supplying extra oxygen as it increases the flame velocity, flame temperature, lean flammability limit, flame stability, and available energy. Salzano et al. [14] and Cammarota et al. [4] report that, increase in flame velocity and flame temperature can lead to a flame propagation which is not deflagration but it is combustion induced rapid phase transition. An increased laminar burning velocity due to oxygen enrichment leads to increase in maximum pressure and rate of pressure rise as explained by Di Benedetto et al. [7]. These factors limit the level of oxygen enrichment in engines to the optimum level of up to 30% by volume. Above 30% by volume of oxygen enrichment causes uncontrollable combustion.

Oxygen enhanced combustion has become one of the most attractive combustion technologies in the last decade. Significance of oxygen enhanced combustion is increasing due to strict environmental regulations and awareness on pollution. Thus the purpose of this study is to investigate the effects of oxygen enriched combustion on a single cylinder, direct injection, and four stroke diesel engines with different levels of oxygen concentrations.

## 2. Experimental methods

### 2.1. Engine specification

A single vertical cylinder, air cooled, four stroke, compression ignition, direct injection diesel engine having the following specifications in Table 1 was used for conducting the experiments.

### 2.2. Experimental setup

The experimental setup used in this research is demonstrated in Fig. 1. Oxygen is added from the oxygen cylinder to the engine intake system just before the air box in order to allow sufficient time for mixing. A flow control valve attached to the oxygen cylinder was used to control the oxygen concentration at volume fractions from 21% baseline to 27% high level.

The oxygen concentration is measured with an Oxygen analyzer fitted between air box and inlet manifold of the engine. The test engine is coupled to Magtrol (model-4WB15)-eddy current dynamometer. The main measuring instruments used were; a mass balance with an accuracy of 0.01 g to measure the fuel flow rate, a bomb calorie meter to measure the calorific value of fuel, a thermocouple to measure the temperature of exhaust gas, inlet air, a TDC marker (a magnetic pickup) and an rpm indicator. A Kistler piezo electric transducer measures the combustion chamber pressure (it is a mean value of 50 consecutive cycles) with an increment of 1° crank angle using an AVL data acquisition system (AVL indicom compact). Exhaust gases were measured by HORIBA MEXA 548L five gas analyzer and gases are measured based on non-dispersive infrared principle. The Analyzer measures nitrogen oxides (NOx) with a resolution of 1 ppm, total unburned hydrocarbon (HC) also at a resolution of 1 ppm, and carbon monoxide (CO) with a resolution of 0.01%. An AVL smoke meter of model AVL 437C is used to measure the smoke opacity with a range of 0 to 99.99% of smoke opacity with the resolution of 0.01%.

**Table 1**
Specifications of the engine used for experimentation.

| Engine | Specifications |
|---|---|
| Type | Kirloskar TAF 1 |
| Number of cylinders | 1 |
| Cubic capacity | 0.662 Liters |
| Bore × Stroke | 87.5 × 110 mm |
| Compression ratio | 17.5:1 |
| Rated power | 4.33 kW |
| Rated speed | 1500 rpm |
| Fuel injection | Direct injection |
| Injection timing | 21 degree btdc[a] |
| Injection pressure | 230 bar |

[a] Before top dead center.

### 2.3. Experimental procedure

The engine parameters, air flow rate, fuel flow rate and emission parameters, unburned hydrocarbon, carbon monoxide, nitrogen oxide and smoke opacity are measured using the above instruments. Test conditions were designed to investigate the effect of oxygen concentration on engine performance and emission characteristics. Tests were carried out at different loadings starting from no load to the rated capacity of the engine with an incremental loading of 20%, at a constant speed of 1500 RPM. Consistency and repeatability of the engine operating conditions were ensured by first running it for approximately 10 minutes at 1500 rpm at 50% load until exhaust gas temperature reached 250 °C. Once these conditions are achieved, the test engine was brought to the required test condition and then allowed for at least two minutes before collecting the data. Four different levels of oxygen concentration, 21% (ambient air), 23%, 25% and 27% by volume, were used for the inlet air. The fuel injection timing and injection pressure were maintained at original setting while adding oxygen to the intake air.

## 3. Results and discussions

The prime objective of this research is to investigate the engine performance and emission parameters affected by the use of oxygen enrichment. The performance and emission values are reported at six operating points.

Fig. 2 illustrates the effect of oxygen enrichment on the in-cylinder pressure. A maximum of 2 to 4 percent increase in peak cylinder pressures is achieved in 23 to 27 percent oxygen enriched air than ambient air at part load conditions. These indicate a feasibility of increasing the net engine power by reasonable level. There is formation of local stoichiometric mixtures rather than rich premixed mixtures, which leads to rising in cylinder temperature and pressure.

The brake thermal efficiency, which is the ratio between the measured brake power to the product of the fuel flow rate and its calorific value, were calculated and plotted against different loads as shown in Fig. 3. From an ideal perspective, the brake thermal efficiency is affected by compression ratio and the thermodynamic properties of the working mixture. Compression ratio is fixed in this study; thermodynamic properties of the mixture however changed due to the addition of oxygen. An increase in oxygen concentration increases the mixture ratio of specific heats, which in essence increases the potential to convert the mixtures thermal energy to work energy.

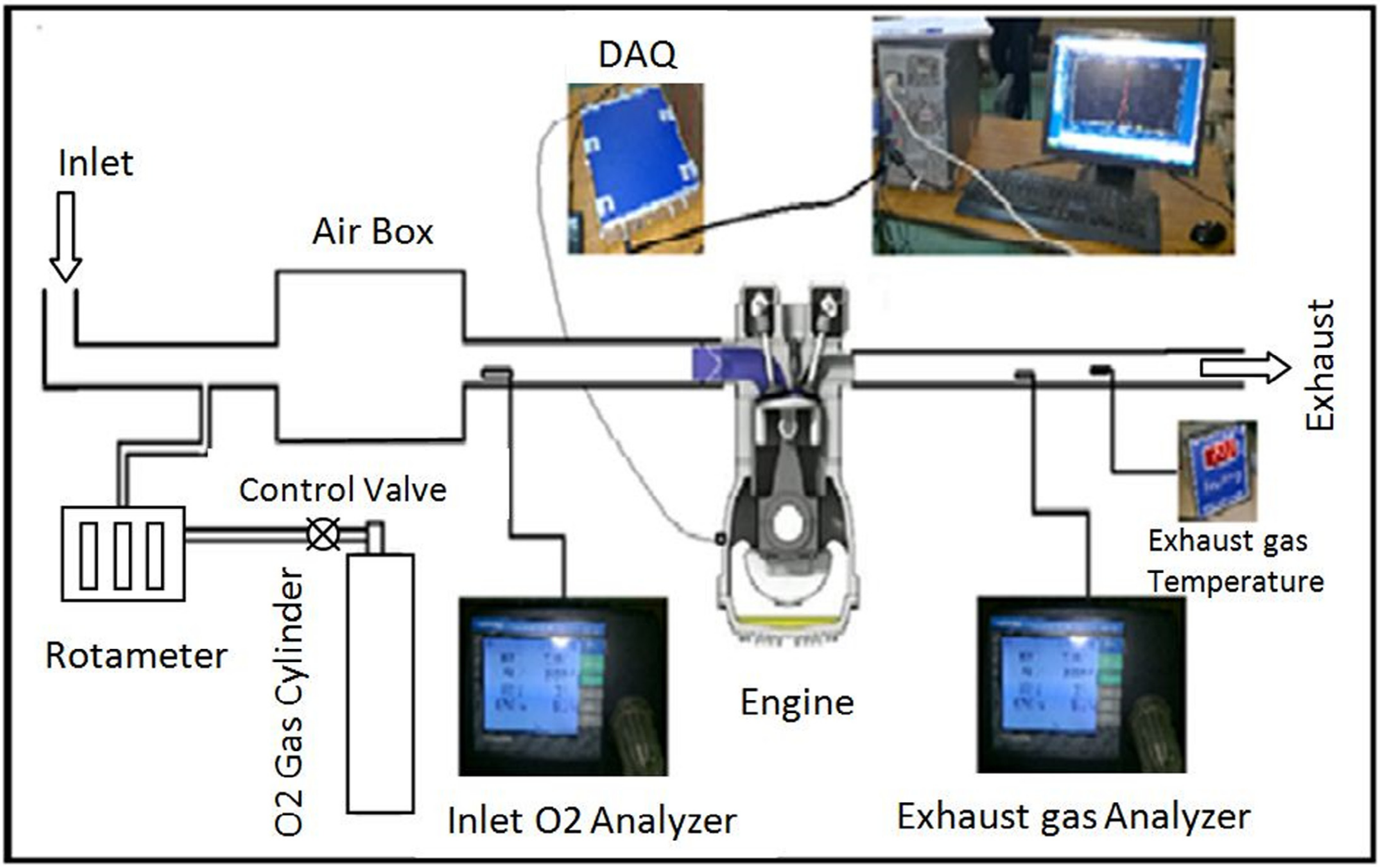


**Fig. 1.** Schematic diagram of experimental setup.

There is about 4 to 8 percent increase in brake thermal efficiency throughout all levels of oxygen enrichment.

The increase in exhaust gas temperature with increased load and oxygen concentration as shown in Fig. 4 was due to increase in reaction rate, flame velocity and increased heat release rate as compared to heat loss rate [15]. The exhaust gas temperature for all oxygen concentrations were increased considerably.

The brake specific fuel consumption is the ratio of rate of fuel consumption to brake power produced, an important parameter that reflects how good the engine performance is. For a fixed hydrogen

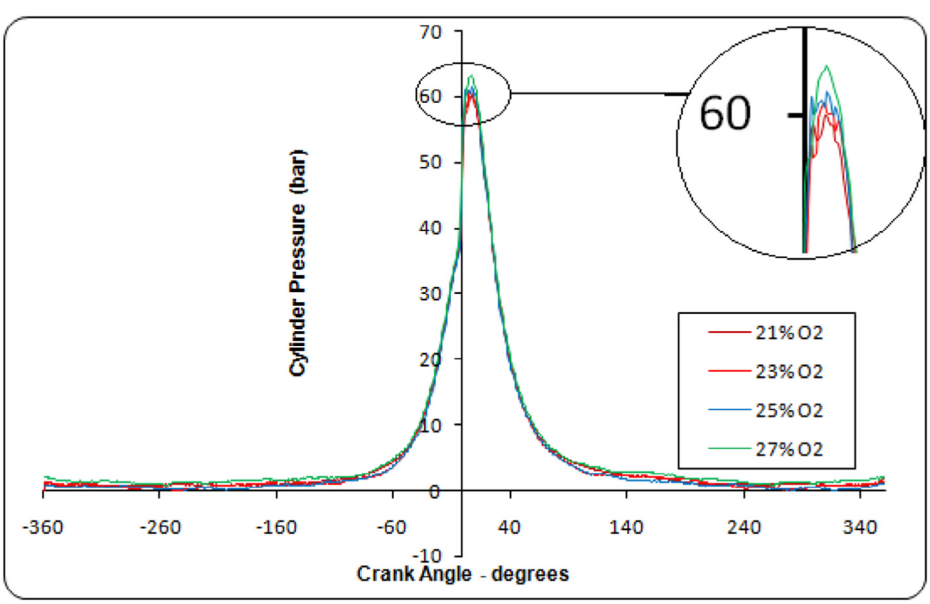


**Fig. 2.** Cylinder pressure in bar as a function of crank angle in degrees at 50% load.

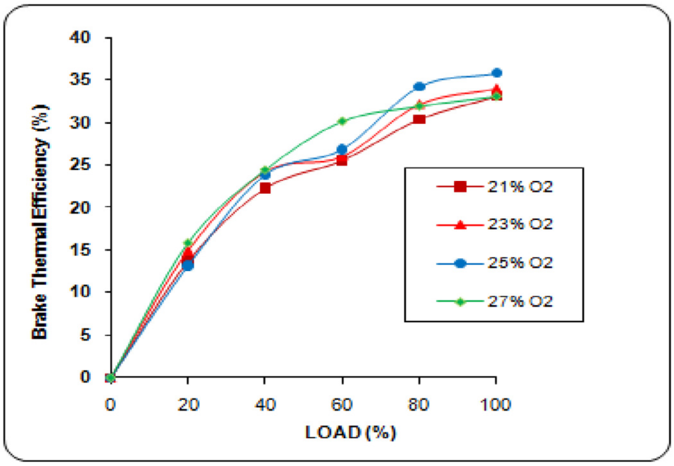


**Fig. 3.** Brake thermal efficiency in percent as a function of percentage of load.

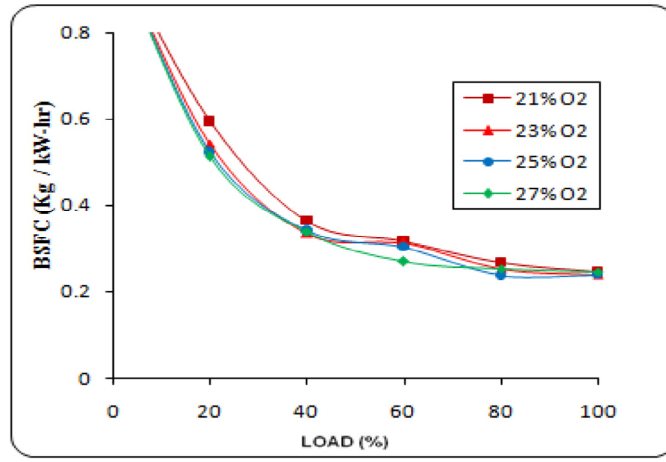


**Fig. 5.** Brake specific fuel consumption in Kg/kW-hr as a function of percentage of load.

to carbon molar ratio (*H*/*C*), the stoichiometric air–fuel ratio decreases when the oxygen concentration in air increases. This means that less air is required for complete combustion of diesel fuel. When air mass flow is constant, as in these experiments, the additional oxygen was used to burn diesel and improves combustion. There is about 5 to 12 percent decrease in specific fuel consumption with increase in oxygen concentration from 21 to 27 percent as illustrated in Fig. 5.

Six principle mechanisms that are believed to be responsible for hydrocarbon emissions are crevices, oil layers, deposits, liquid fuel, flame quench and exhaust valve leakage. When liquid fuel did not find sufficient oxygen to burn prior to the end of combustion, hydrocarbon is formed in the exhaust. Since oxygen enrichment ensures additional oxygen inside the combustion chamber more complete combustion is possible and it lowers the hydrocarbon level in the exhaust. Oxygen enrichment can decrease the quenching distance of the mixture [21] as it was found to be a decreasing function of flame temperature. It is well known that the flame temperature increases in the case of oxygen enrichment [7] and this allows the flame to propagate much closer to the cylinder wall and reduce HC emissions. The hydrocarbon emissions were reduced to a minimum of 10% at 23% oxygen to a maximum of 40% at 27% oxygen enrichment levels as seen in Fig. 6.

CO formation mechanism is well established and it is mainly due to unavailability of enough oxygen for complete oxidation. CO concentration is reduced to 15% at full load to 55% at no load and 27% oxygen enrichment as seen in Fig. 7. The extra oxygen atom which is present in the mixture plays an important role in reducing the CO values. Combustion efficiency, although not reported in this article is assumed to be higher for oxygen enhanced combustion [1,2] than ambient air combustion and this was considered to play a role in reducing HC and CO emission as well as increasing thermal efficiency.

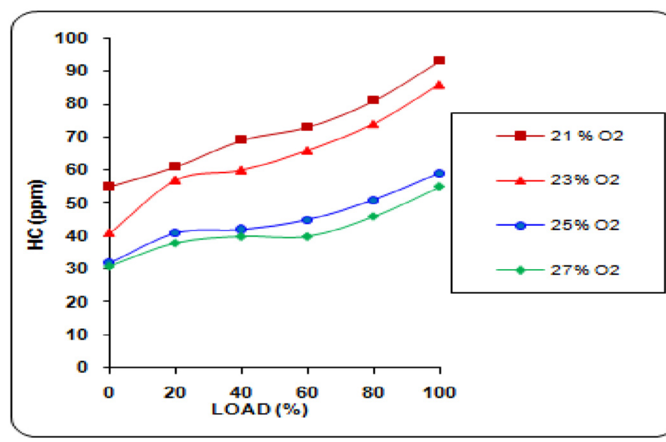


**Fig. 6.** Hydro carbon emissions in ppm as a function of percentage of load.

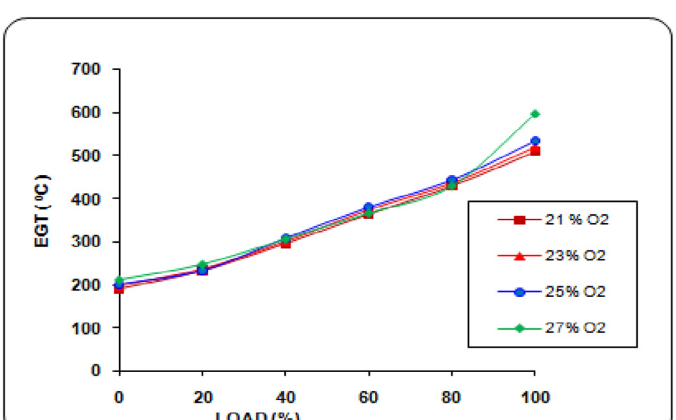


**Fig. 4.** Exhaust gas temperature in °C as a function of percentage of load.

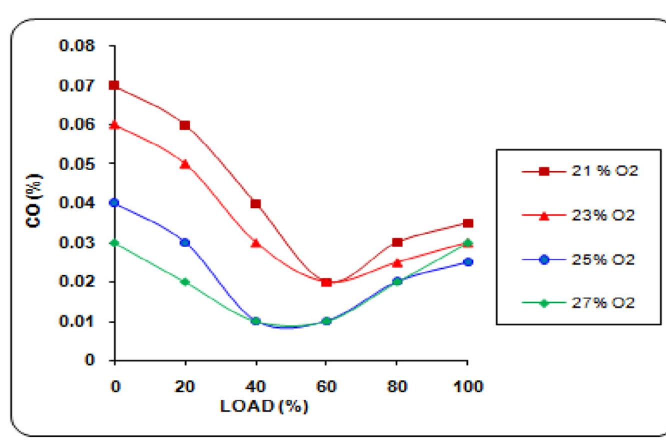


**Fig. 7.** Carbon monoxide emissions in percentage as a function of percentage of load.

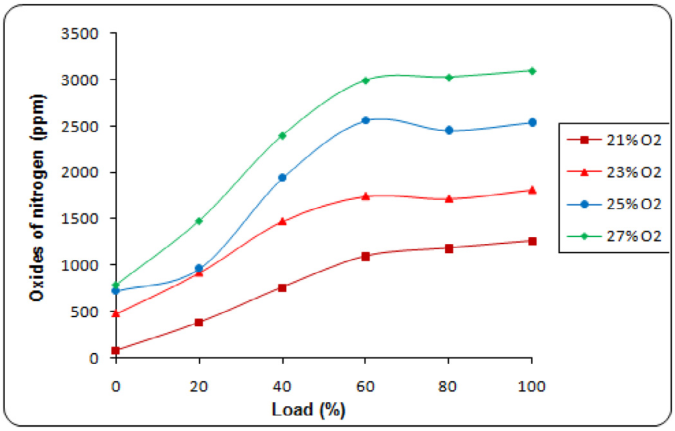


**Fig. 8.** Oxides of nitrogen emission in ppm as a function of percentage of load.

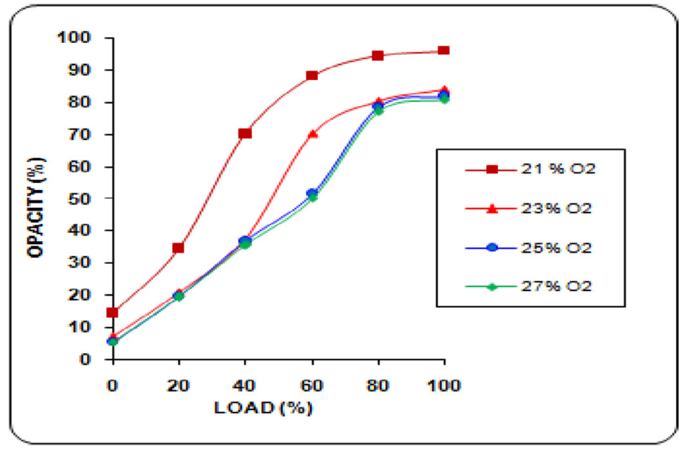


**Fig. 9.** Smoke Opacity in percentage as a function of percentage of load.

NO is the major component of NOx in diesel engines and it is the reaction product of nitrogen at high temperature and oxygen enrichment simultaneously. Two major NO formation mechanisms are thermal NO and Prompt NO. However prompt NO is prevalent only in fuel rich systems and it is not a major source of NO for diesel engines. Only thermal NO based on Zeldovich's mechanism is predominant and it is shown as; $O + N_2 \leftrightarrow NO + N$, $N + O_2 \leftrightarrow NO + O$, $N + OH \leftrightarrow NO + H$. Higher post-flame temperatures and oxygen concentrations during the combustion process results in high thermal NO formation rates [6]. When the oxygen level is increased to 27% the NOx level increases by three times the ambient air as it is shown in Fig. 8. This is the major drawback of oxygen enriched combustion; however, this can be controlled and kept within the reasonable limit by adjusting the fuel injection timing, after treatment techniques [17,19].

One of the promising results from oxygen enrichment is the significant decrease in smoke density in the exhaust. Agglomeration of soot particle in the diesel exhaust is the major source of smoke in diesel engine. It is formed mainly due to incomplete combustion of fuel hydrocarbons and some is contributed by lubricating oil. Soot formation is strongly dependent on the stoichiometry, temperature, pressure and mixing [18]. Soot in the exhaust gas is dominated by soot formation as well as oxidation. One of the main effects of oxygen enrichment is to increase oxygen–fuel ratio, which in turn improves the oxidation of fuel and suppress the soot formation. Oxygen enrichment also reduces the ignition delay, meaning higher burning rate and shorter combustion duration [15] which further reduces soot formation. The minimum reduction of smoke opacity in oxygen enrichment is 15% at full load with 27% oxygen enrichment, while the maximum reduction is 60% at no load 27% oxygen enrichment. Consistently there is reduction of smoke opacity levels at all loads and oxygen concentration levels as reported in Fig. 9.

## 4. Conclusions

The effect of oxygen enrichment on engine performance and emission characteristics are studied using single-cylinder; direct injection diesel engine with multiple oxygen concentrations and the results can be summarized as follows:

- The combustion performance of the engine is greatly improved and it is noticed from increased brake thermal efficiency and reduced brake specific fuel consumption. The main reason for this is due to higher combustion rate, which in turn due to higher flame temperature and burning velocity. The air–fuel mixture becomes progressively leaner with increase in oxygen percentage which is one of the reasons for lower brake specific fuel consumption.
- Favorable mechanism for the formation of carbon monoxide and unburned hydrocarbon is reduced by oxygen enrichment, which in turn results in complete combustion of fuel.
- Reduction in smoke opacity level at all oxygen concentrations suggests lower particulates from the oxygen enhanced combustion.
- A high value of NOx emissions with increasing oxygen concentration is a drawback of the technology. More experiments are needed to develop a method to control the NOx levels by retarding the injection and after treatment techniques.

Overall there is tremendous potential in utilizing oxygen enrichment in diesel engine for automotive application as it showed improved engine performance and lower emissions with future works to develop membrane technology that can be incorporated in intake air system for oxygen enrichment and further studies to control oxides of nitrogen for optimum performance.

## References

[1] G.L. Borman, K.W. Ragland, Combustion Engineering, McGraw-Hill, Inc., 1998, pp. 155–162, 153, and 226.
[2] C.E. Baukal, Oxygen-Enhanced Combustion, second ed., CRC Press, 2013.
[3] J.B. Heywood, Internal Combustion Engine Fundamentals, McGraw-Hill Book Co, 1988.
[4] F. Cammarota, A. Di Benedetto, P. Russo, E. Salzano, Experimental analysis of gas explosions at non-atmospheric initial conditions in cylindrical vessel, Process Saf. Environ. Prot. 88 (5) (2010) 341–349.
[5] R.L. Cole, R.R. Sekar, F.S. Stodosky, T.J. Marciniak,1990. Technical and economic evaluation of diesel engine with oxygen enrichment and water injection. ASME paper No. 90-ICE-1.
[6] J.S. Chin, Analysis of the effect of oxygen addition on minimum ignition energy, J. Energy 7 (1983) 710–715.
[7] A. Di Benedetto, F. Cammarota, V. Di Sarli, E. Salzano, G. Russo, Reconsidering the flammability diagram for $CH_4/O_2/N_2$ and $CH_4/O_2/CO_2$ mixtures in light of combustion-induced Rapid Phase Transition, Chem. Eng. Sci. 84 (2012) 142–147.
[8] R.J. Donahue, D.E. Foster, Effects of oxygen enhancement on the emissions from a diesel via manipulation of fuels and combustion chamber gas composition. Society of Automotive Engineers Transactions, J. Fuels Lubricants 109 (2000) 334–349, SAE 2000-01-0512.
[9] H.C. Watson, E.E. Milkins, G.R. Rigby,1990. A new look at oxygen enrichment 1) The diesel engine. Society of Automotive Engineers, technical paper series, 900344.
[10] N. Lida, Y. Suzuki, G.T. Sato, T. Sawada,1986. Effects of intake oxygen concentration on the characteristics of particulate emissions from a DI engine. Society of Automotive Engineers, 861233.
[11] W.W. Marr, R.R. Sekar, R.L. Cole, T.J. Marciniak, D.E. Longman,1993. Oxygen-enriched diesel experiments with a low-grade fuel. Society of Automotive Engineers, 932805.

[12] R.B. Poola, R. Sekar, Reduction of NO and particulate emissions by using oxygen-enriched combustion air in a locomotive diesel engine, J. Eng. Gas Turbines Power 125 (2003) 524.
[13] R.B. Poola, K.C. Stork, R. Sekar, K. Callaghan, S. Nemser, 1998. Variable air composition with polymer membrane – a new low emissions tool. Society of Automotive Engineers, Tech. Paper Ser. No. 980178.
[14] E. Salzano, A. Basco, F. Cammarota, V. Di Sarli, A. Di Benedetto, Explosions of syngas/$CO_2$ mixtures in oxygen-enriched air, Ind. Eng. Chem. Res. 51 (22) (2012) 7671–7678.
[15] R.R. Sekar, W.W. Marr, J.E. Schaus, R.L. Cole, T.J. Marcihiak, J.N. Eustis, 1990. Cylinder pressure analysis of a diesel engine using oxygen-enriched air and emulsified fuels. Society of Automotive Engineers, 901565.
[16] J. Song, V. Zello, A.L. Boehman, F.J. Waller, Comparison of the impact of intake oxygen enrichment and fuel oxygenation on diesel combustion and emissions, Energy Fuels 18 (2004) 1282–1290.
[17] K.A. Subramanian, A. Ramesh, 2001. Experimental investigation on the use of water diesel emulsion with oxygen-enriched air in a DI diesel engine. Society of Automotive Engineers, 2001-01-0205.
[18] D.R. Tree, K.I. Svensson, Soot processes in compression ignition engines, Prog. Energy Combus. Sci. 33 (2007) 272–309.
[19] K.S. Virk, U. Kokturk, C.R. Bartels, 1993. Effects of oxygen-enriched air on diesel engine exhaust emissions and engine performance. Society of Automotive Engineers 931004.
[20] H.C. Watson, G.R. Rigby, Oxygen Enrichment – A Method for Reduced Environment Impact and Improved Economics, Fuels for Automotive & Industrial Diesel Engines, Institute of Mechanical Engineers, 1990, pp. 91–99.
[21] Y. Liang, G. Shu, H. Wei, W. Zhang, Effect of oxygen enriched combustion and water–diesel emulsion on the performance and emissions of turbocharged diesel engine, Energy Conv. Manage. 73 (2013) 69–77.