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EFFECT OF OXYGEN ENRICHMENT ON COMBUSTION CHARACTERISTICS OF A DIESEL ENGINE

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Abstract

An investigation on the effect of oxygen enriched air on the diesel engine combustion characteristics is carried out under part load and full load conditions. The present investigation focuses on the combustion characteristics such as heat release, the delay period and the combustion duration of a single cylinder, four-stroke, direct injection diesel engine when the intake air is enriched with 23%, 25% and 27% of oxygen by volume. The experimental results have revealed that increasing oxygen content in air leads to faster burn rates and shorter ignition delays. There is also an increase in peak cylinder pressure and rate of pressure rise which can be optimized to control emissions and also to improve the engine performance. An improvement in thermal efficiency is observed due to improved combustion performance. The experimental outcomes exposed that when diesel engine is operated with oxygen enriched air an improvement in combustion characteristics is apparent.

Keywords: Diesel engine, Oxygen enrichment, Combustion, Heat release, Delay period.

1. Introduction

It is generally accepted that diesel engines are designed to operate with an excess air in the region of 15% to 40%. This helps to find the necessary oxygen for complete combustion. Therefore, the engine size becomes bigger for a given output and the air-fuel mixture will be heterogeneous in nature. One of the main aims of the diesel engine designer is that air-fuel ratio should be as close to stoichiometric as possible while operating at full load at the same time giving a better mean effective pressure and thermal efficiency.

Greek Symbols

η_{BT}	Brake thermal efficiency in percentage
θ	Crank angle in degrees

Abbreviations

AVL	Anstalt Für Verbrennungskraftmaschinen List
bTDC	Before Top Dead Centre
CA	Crank Angle
CDM	Crank Degree Marker
CO	Carbon Mono Oxide
EGT	Exhaust Gas Temperature
NOx	Oxides of Nitrogen
OEA	Oxygen Enriched Air
TDC	Top Dead Centre
UBHC	Unburned Hydrocarbon

To ensure a complete combustion even with latest technology the engines must operate in excess air. That is, more air carrying 21% oxygen by volume was passed through the intake valve than the chemically required for complete combustion and this process ensures that nearly all fuel molecules receive required oxygen for complete combustion. Excess air inside the combustion chamber helps the mixing of fuel with air and ensures complete combustion. However, this additional air, wastes heat energy by carrying the heat in the exhaust gases. So sufficient oxygen must be provided during the combustion process, for a complete conversion of carbon and hydrogen into carbon-di-oxide or else particulates and carbon monoxide formed will cause increased exhaust emissions.

A number of analytical and experimental studies [1-24] have demonstrated the benefits of using oxygen enhanced intake air in diesel engines. The fuel consumption rate, the power output and the exhaust temperature are varying marginally. *UBHC* and CO emission levels decrease and smoke levels drop substantially, while NOx emissions increase pro-rata with the oxygen added.

Watson et al. [1] experimentally investigated that the inferior quality fuels can be used in the engines without affecting the overall performance of the engines. They reported a significant reduction in particulates and increased thermal efficiency. Marr et al. [2] continued the work on low grade fuel and got the similar results.

Ghojel et al. [3] studied the effect of partial pressure of oxygen on the indirect injection diesel engine combustion and their research revealed that enriching the intake air with oxygen led to decrease in ignition delay and reduced combustion noise. One of the limitations of using OEA was increased NOx emission, Sekar et al. [4] proved that NOx can be reduced by oxygen enrichment with emulsified diesel fuel with considerable decrease in smoke and particulate matters. Virk et al. [5] tried to reduce NOx emission by retarded injection timing with low levels of OEA and by this method NOx levels were kept at the same value as the ambient-air, while particulates and smoke emissions were reduced by 15 to 30%.

Donahue et al. [6] investigated the potential of OEA with oxygenated base fuel with 20% methyl-butyl ether. The results show that, whether oxygen is supplied through OEA or oxygenated fuel reduces particulate matter and its effectiveness depends on the local concentration of oxygen in the fuel plume. Cole et al. [7] studied the technical and economic feasibility of diesel engines for stationary co-generation application with OEA using computer simulations. They studied the four methods of oxygen enrichment out of these the pressure swing adsorption and membrane enrichment are suitable for a stationary engine. Economic viability of the system depends on moving to a cheaper low-grade fuel with increased power production.

Chin [8] has studied the effect of injected oxygen into the air stream of an engine inlet manifold on ignition energy required. The test results indicate the minimum ignition energy requirement, especially at reduced pressure. Song et al. [9] have observed that both OEA and oxygenated fuel via linear structured oxygenated molecules are effective in reducing diesel particulate matter. However, NOx emissions are generally increased with OEA due to increased availability of atomic oxygen and also due to attainment of higher temperature during lean operation which enhances the kinetic for thermal NOx formation [10]. This was clearly observed in the works of Jianxi et al. [11] and Baskar et al. [12].

Perez et al. [13] tested a single cylinder, naturally aspirated, air cooled Diesel engine at simulated high-altitude condition and found that power output depended mainly on engine load and was not increased by OEA. Oxygen enrichment is also effective in preventing deterioration of brake specific fuel consumption in simulated altitude.

Salzano et al. [14] and Cammarota et al. [15] 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. [16]. These factors limit the level of oxygen enrichment in engines to the optimum level of 30% by volume and above these levels causes uncontrollable combustion.

The increasing nitrogen oxide emissions can be reduced by using emulsified diesel as reported by Subramanian et al. [17] and Youcai Liang et al. [18]. The fact that the oxygen enriched combustion results in lower ignition delay promotes the use of water diesel emulsion. Yingying Lu et al. [19] studied the effect of lower oxygen concentration and found that 17% OEA causes increase in soot and CO exhaust because lower temperature in the later stages of combustion. Mohsen et al. [20] illustrate that oxygen enrichment is an effective way to reduce knock tendency of pilot ignited natural gas diesel engine at maximum load.

Thus, oxygen enrichment has become one of the most attracting combustion technologies in the last decade. Significance of oxygen enhanced combustion is increasing due to strict environmental regulations and awareness on pollution. Most of the literature available concentrate mostly on performance and emissions characteristics of an engine and a very few literatures discusses about combustion characteristics of a single cylinder diesel engine. So, a detailed discussion is required on combustion characteristics of the OEA technology. Thus, the purpose of this study is to investigate the combustion characteristics of oxygen enhanced combustion on a direct injection, four-stroke and single cylinder internal combustion engine with oxygen concentration varied from 21% to 27% by volume.

2. Experimental Methods

2.1. Engine specification

The engine selected for the investigation is a single cylinder, four-stroke, naturally aspirated direct injection diesel engine. The key specifications of the test engine are provided in Table 1.

Table 1. Test engine specifications.

Parameters	Specification
Engine type	Kirloskar TAF 1
Number of cylinders	1
Cubic capacity	0.662 liters
Bore × stroke	87.5 × 110 mm
Compression ratio	17.5
Rated power	4.47 kW
Injection pressure	230 bar
Injection timing	21 deg bTDC
Rated speed	1500 rpm
Governing	Class B1
Cooling method	Air cooled

2.2. Testing facility

The test engine was coupled to an eddy current dynamometer and the torque was measured by means of a strain gauge load cell connected to the lever arm. The engine speed was measured by means of a magnetic pick-up and the intake air mass flow rate was measured by using a hot wire anemometer. The installation of the experimental setup is shown schematically in Fig. 1.

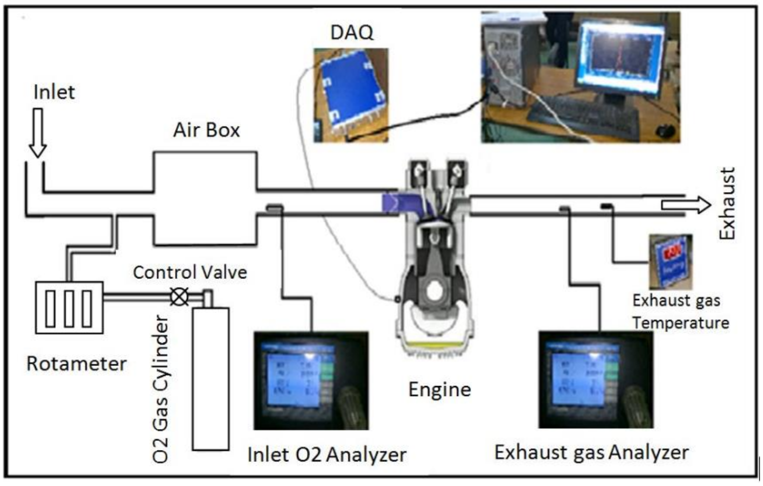

Fig. 1. Schematic diagram of the test engine with measuring instruments.

Oxygen enrichment of the inlet air was done by supplying oxygen from a cylinder into the air box where it gets mixed with the atmospheric air. The required 21%, 23%, 25% and 27 percentage of oxygen enrichment are obtained by controlling the oxygen flow rate by a rotameter and continuously monitoring through oxygen sensor. The inlet air and exhaust gas temperatures of the engine were measured using ‘K type’ thermocouple with digital monitor. Diesel fuel consumption rate was recorded by the gravimetric method using a mass balance with an accuracy of 0.01g. Exhaust gases were measured by HORIBA MEXA-584L five gas analyser. It measures CO, HC, NO, and CO_2 by non-dispersive infrared: NDIR principle. O_2 measurement and air-to-fuel ratio by carbon balance method or Brettschneider method [25]. High speed data from an engine comprising of cylinder pressure and crank angle were acquired using AVL combustion measurement system with the Indicom Mobile software user interface supplied by AVL India. A Kistler 601A type piezoelectric pressure sensor with a range of 0 to 250 bar and a sensitivity of 16 pC/bar was mounted in the combustion chamber and the signal was amplified using a charge amplifier. All these acquired data are recorded at a resolution of 1-degree crank angle on the falling edge of the CDM signal from an AVL optical encoder and it is mounted directly on the crankshaft of the engine. A single pulse per revolution signal supplied by the encoder is used to mark TDC and trigger data acquisition of fifty consecutive four stroke cycles.

2.3. Test procedure

During this investigation, combustion data were obtained under steady state operating conditions at six different loads corresponding to 0%, 20%, 40%, 60%, 80% and 100% of full load condition 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 the exhaust gas temperature reached 250 ^{0}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. Based on literature studies inlet oxygen concentration levels of 21% (ambient air), 23%, 25% and 27% by volume are used. For each level of oxygen concentration, the engine was subjected to different loading conditions (by percent) and the test data were recorded at each operating condition considered.

3. Results and Discussion

The results of the experimental investigation are presented and the important observations are discussed in detail in the following paragraphs.

Figure 2 shows the in-cylinder pressure versus crank angle data over the four strokes of the engine operating cycle for different oxygen enrichment levels. The pressure curve helps to obtain quantitative information on the progress of combustion. As observed in literatures [5, 13, 17] there is little variation in the progress of combustion except a considerable rise in peak pressure. In the present work, the maximum in-cylinder pressure was noted with 27% of oxygen enrichment (67.132 bar) occurring at 7^{0}CA after TDC, whereas for ambient condition the peak pressure (64.036 bar) occurred at same 7^{0}CA after TDC. Figure 3 shows that peak pressure of oxygen enriched combustion can increase up to 5% compared to conventional ambient air operation at all loading conditions.

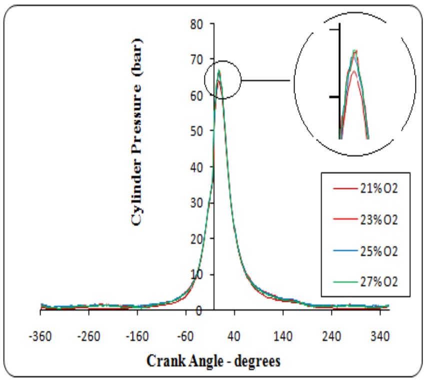

Fig. 2. In Cylinder pressure (bar) vs. rank angle (degrees) at full load.

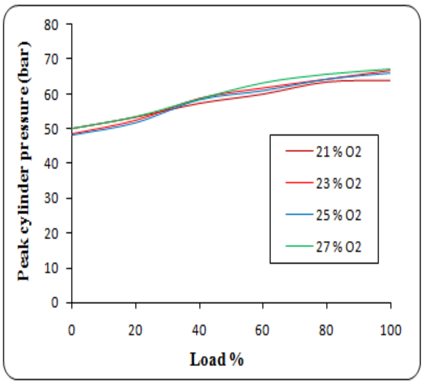

Fig. 3. Peak cylinder pressure (bar) vs. load (percent).

The heat release rate traces from Fig. 4 shows that the initial premix burn mode of combustion is smaller with oxygen enrichment, due to smaller delay period. There is a peak for the premixed combustion at the earlier combustion phase at 21% of OEA, while the combustion shows a strong mixing controlled combustion process at 25% of OEA and the peak of premixed combustion is observable at all levels of OEA. But for 25% of OEA it shows a little larger peak of premixed combustion phase due to short ignition delay. However, the peak heat release rate increases with increase of OEA. The peaks of heat release rate increase are 10% to 30% of OEA compared with the ambient air at all loading conditions. The above values indicate a faster combustion process with increased OEA, and as a result, a higher thermal efficiency is expected.

Due to vaporization effects, the cumulative heat release curve in Fig. 5 exhibit negative values before the start of combustion in the engine. The starting of combustion takes place as the angle value at which the cumulative heat release changes from negative to positive. As seen in Fig. 5 the combustion of OEA starts a little earlier than ambient air condition and heat release rate also quicker which in turn causes combustion duration of OEA to be shorter than normal combustion.

One of the most interesting observations of mass fraction burned profile is its half value - it is suggested that the optimum efficiency of the engine combustion is achieved if 50% energy conversion occurs at 8 to 10 ^{0}CA after TDC [24]. The analysis of Fig. 6 shows that the crank angle location of half value of mass fraction burned are 8 or 9 ^{0}CA after TDC for all levels of OEA. This helps to improve the thermal efficiency of an engine.

Figure.7 illustrates the variation of rate of pressure rise versus crank angle. Rate of pressure rise analysis in diesel engine study is often considered as a measure of combustion generated noise. However, the acceptable limit for maximum rate of pressure rise is subjective [22]. A maximum rate of pressure rise of 7.76 bar/ ^{0}CA occurs at 4 ^{0}CA before TDC for 27% oxygen enrichment and a minimum rate of pressure of 6.71 bar/ ^{0}CA occurs at 5 ^{0}CA before TDC for ambient air condition. The low rate of combustion takes longer time for completion of combustion, which necessitates the fuel injection at an early point while higher rate of combustion results in high rate of pressure rise producing higher peak pressure point closer to TDC. But this can be controlled by retarding the injection which in turn helps to reduce the NOx emissions [11].

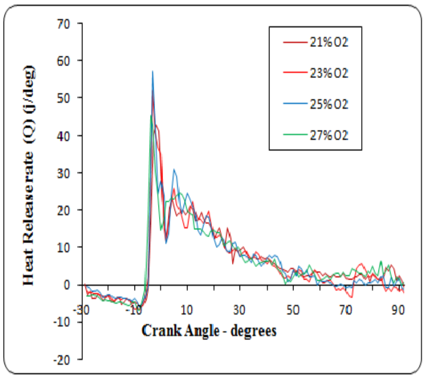

Fig. 4. Heat release rate (J/deg) vs. crank angle (degrees) at full load.

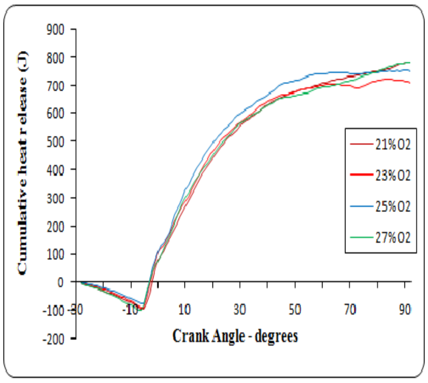

Fig. 5. Cumulative heat release (J) vs. crank angle (degrees) at full load.

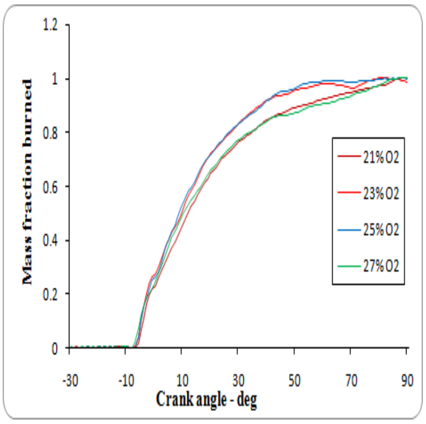

Fig. 6. Mass fraction burned vs. crank angle (degrees) at full load.

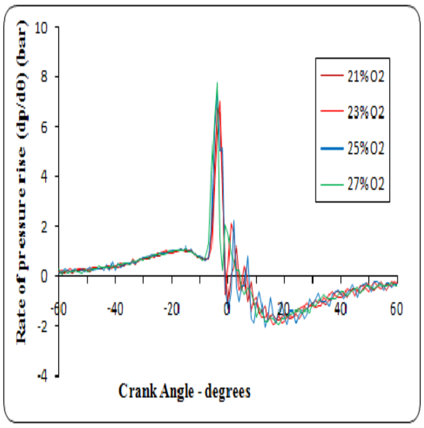

Fig. 7. Rate of pressure rise (bar) vs. crank angle (degrees) at full load.

Oxygen enriched combustion changes the two stages of typical diesel combustion. As it is seen in Fig. 8 shorter delay period causes shorter premixed and mixing controlled combustion. Since delay period is shorter, the chances of knocking are also reduced due to low accumulation of fuel during this period. It is also observed in Fig. 9 that the combustion duration is reduced to a maximum of 16 ^{0}CA at 0% load to a minimum of 6 ^{0}CA at full load.

It is observed from Fig. 10 that the brake thermal efficiency increases by 4% to 8% throughout all levels of oxygen enrichment. Brake thermal efficiency is a function of compression ratio and thermodynamic properties of the working mixture. Compression ratio is not altered in this study; however thermodynamic properties of the air-fuel mixture changed due to the addition of oxygen. An increase in oxygen concentration increases the mixture ratio of specific heats, which in essence increases the thermal efficiency of an engine. Fig. 11 clearly indicates an increase in exhaust gas temperature at all levels of oxygen enrichment. This is mainly due to shorter ignition delay, which in turn causes the increased flame temperature. The high flame temperature increases the NOx formation but it also helps to reduce soot generation [21].

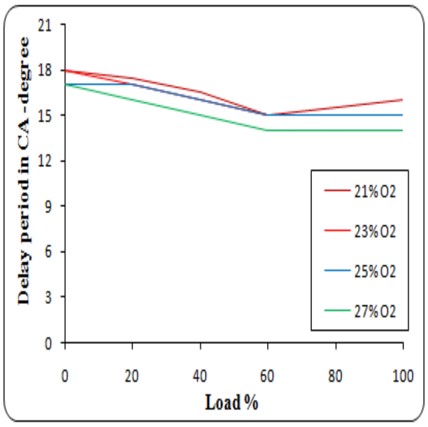

Fig. 8. Delay period (CA) vs. load (%).

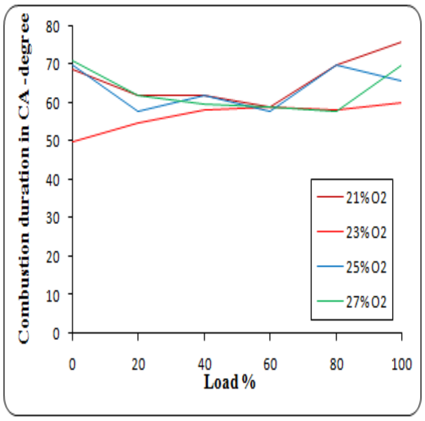

Fig. 9. Combustion duration (CA) vs. load (%).

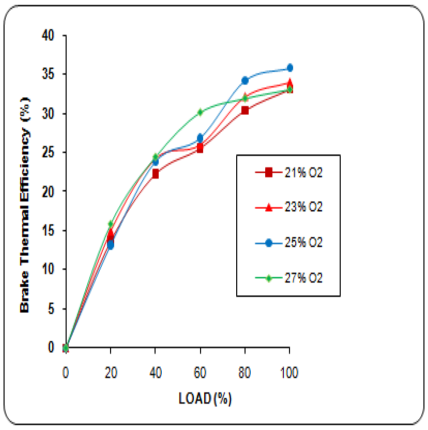

Fig. 10. Brake thermal efficiency (percent) vs. load (percent).

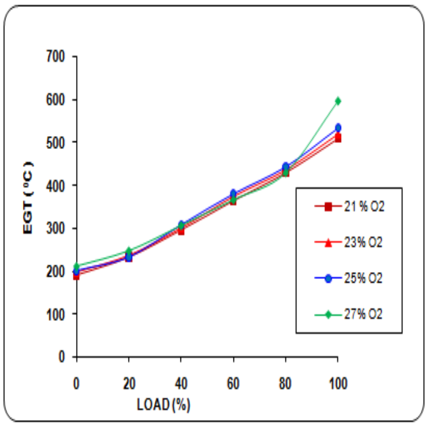

Fig. 11. Exhaust gas temperature (°C) vs. load (percent).

4. Conclusions

An investigation has been made to study the effects of oxygen enriched combustion in the diesel engine combustion characteristics. The concluding observations from the present study are given below.

- An increased heat release rate and peak cylinder pressure can be utilized to increase the power output or downsize the engine.

- Oxygen enriched combustion leads to a shorter delay period and higher diffusion burn rates which in turn causes faster completion of the combustion process. These effects in turn permit the fuel injection timing to be retarded to control the NO_x emissions.
- Shorter ignition delay increases the flame temperature, which in turn will increase NOx emissions and at the same time a high flame temperature will reduce the soot formation.
- The faster combustion process caused by increasing the heat release rate with increased *OEA* improves the thermal efficiency.

Overall there is a tremendous potential in utilising oxygen enrichment in diesel engine for automotive application. With the future work to develop membrane technology that can be incorporated in the intake air system for oxygen enrichment. Further study is possible to adjust the injection timing for optimum performance and after treatment for reduced NOx emissions.

References

1. Watson, H.; Milkins, E.; and Rigby, G. (1990). A new look at oxygen enrichment 1) The Diesel engine. *Society of Automotive Engineers*, Technical Paper 900344.
2. Marr, W.W.; Sekar, R.R.; Cole, R.L.; Marciniak, T.J.; and Longman, D.E. (1993). Oxygen-enriched diesel experiments with a low-grade fuel. *Society of Automotive Engineers*, Technical Paper 932805.
3. Ghojel, J.; Hilliard, J.; and Levendis, J. (1983). The effect of oxygen enrichment on the performance and emissions of I.D.I. Diesel engines. *Society of Automotive Engineers*, Technical Paper 830245.
4. Sekar, R.R.; Marr, W.W.; Schaus, J.E.; Cole, R.L.; Marcihiak, T.J.; and Eustis J.N. (1990). Cylinder pressure analysis of a diesel engine using oxygen-enriched air and emulsified fuels. *Society of Automotive Engineers*, Technical Paper 901565.
5. Virk, K.S.; Kokturk, U.; and Bartels, C.R. (1993). Effects of oxygen-enriched air on diesel engine exhaust emissions and engine performance. *Society of Automotive Engineers*, Technical Paper 931004.
6. Donahue, R.J.; and Foster D.E. (2000). Effects of oxygen enhancement on the emissions from a diesel via manipulation of fuels and combustion chamber gas composition. *Society of Automotive Engineers Transactions, Journal of Fuels & Lubricants*, 109, 334 – 349.
7. Cole, R.L.; Sekar, R.R.; Stodosky, F.S.; and Marciniak, T.J. (1990). Technical and economic evaluation of diesel engine with oxygen enrichment and water injection. *American Society of Mechanical Engineers*, 90.
8. Chin, J.S. (1983). Analysis of the effect of oxygen addition on minimum ignition energy. *Journal of Energy*, 7, 710 -715.
9. Song, J.; Zello, V.; and Boehman, A.L. (2004). Comparison of the impact of intake oxygen enrichment and fuel oxygenation on diesel combustion and emissions. *Energy* & *Fuels*, 18, 1282 -1290.

10. Poola, R.B.; and Sekar, R. (2003). Reduction of NO and particulate emissions by using oxygen-enriched combustion air in a locomotive diesel engine. *Journal of Engineering for Gas Turbines and Power*, 125, 524-533.
11. Jianxi, Zhou.; Stephane, Richard.; Christine.; Mounaïm-Rousselle.; and Fabrice, Foucher. (2013). Effects of controlling oxygen concentration on the performance, emission and combustion characteristics in a downsized SI engine. *Society of Automotive Engineers*, 2013-24-0056.
12. Baskar, P.; and Senthilkumar, A. (2016). Effects of oxygen enriched combustion on pollution and performance characteristics of a diesel engine. *Engineering Science and Technology - an International Journal*, 19(2016), 438-443.
13. Perez, P.L.; and Boehman, A.L. (2010). Performance of a single-cylinder diesel engine using oxygen-enriched intake air at simulated high-altitude conditions. *Aerospace Science and Technology*, 14(2), 83–94.
14. Salzano, E.; Basco, A.; Cammarota, F.; Di Sarli, V.; and Di Benedetto, A. (2012). Explosions of syngas/CO2 mixtures in oxygen-enriched air. *Industrial & Engineering Chemistry Research*, 51(22), 7671-7678.
15. Cammarota, F.; Di Benedetto. A.; Russo, P.; and Salzano, E. (2010). Experimental analysis of gas explosions at non-atmospheric initial conditions in cylindrical vessel. *Process Safety and Environmental Protection*, 88(5), 341-349.
16. Di Benedetto, A.; Cammarota, F.; Di Sarli, V.; Salzano, E.; and Russo, G. (2012). 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. *Chemical Engineering Science*, 84, 142-147.
17. Subramanian, K.A.; and Ramesh, A. (2001). Experimental investigation on the use of water-diesel emulsion with oxygen- enriched air in a DI diesel engine. *Society of Automotive Engineers*, Technical Paper 2001-01-0205.
18. Youcai, Liang.; Gequn, Shu.; Haiqiao, Wei.; and Wei, Zhang. (2013). Effect of oxygen enriched combustion and water–diesel emulsion on the performance and emissions of turbocharged diesel engine. *Energy Conversion and Management*, 73, 69–77.
19. Yingying, Lu.; Wenbin, Yu.; Yiqiang, Pei.; and Wanhua, Su. (2013). Effects of charge density and oxygen concentration on combustion process: Efficiency and emissions in a high load operation diesel engine. *Society of Automotive Engineers*, Technical Paper 2013-01-0895.
20. Mohsen, M.A.; Basem, A.; Rabee.; and Abdelrahman, H.H. (2013). Effect of adding oxygen to the intake air on a dual-fuel engine performance, emissions, and knock tendency. *Energy Journal*, 61, 612–620.
21. Tree, D.R.; and Svensson, K.I. (2007). Soot processes in compression ignition engines. *Progress in Energy and Combustion Science*, 33, 272–309.
22. Rakopoulos, C.D.; Hountalas, D.T.; and Zannis, T.C. (2004). Operational and environmental evaluation of diesel engines burning oxygen-enriched intake air or oxygen-enriched fuels: A Review. *Society of Automotive Engineers Series*, Technical Paper 2004 - 01-2924.

23. James, M. Sevik; Thomas, Wallner; Scott, Miers; and Jeff, Wasil (2015). Air-to-fuel ratio calculation methods for oxygenated fuels in two-stroke engines: *Society of Automotive Engineers,* Technical Paper 2015-01-0965.
24. Heywood, J.B. (2007). *Internal combustion engine fundamentals*. USA: McGraw-Hill, Inc.
25. Baukal, C.E. (1998). *Oxygen-enhanced combustion*. USA: CRC Press.