Research Article

Journal of Environmental Nanotechnology

Effect of Oxygen Enrichment in the Emission Characteristics of Yttria Stabilized Zirconia Coated Diesel Engine with Alumina Nanoparticle Additives

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Received: 28.11.2024 Accepted: 05.01.2025 Published: 30.03.2025

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ABSTRACT

This work aims to provide a proper solution for the global warming caused by the emission of IC engines. To cope with the emission standard of current emission norms BS-VI, it is necessary to reduce engine emissions at a considerable level. Oxygen enrichment and alumina nanoparticle additives minimize engine emissions such as hydrocarbon, carbon monoxide, nitrogen oxide, and smoke. For oxygen enrichment, Pressure Swing Adsorption (PSA) methods are used. Oxygen enrichment is done at various oxygen concentrations of 21-29%. Uniform distribution of additives with fuel is done through an ultrasonicator. Yttria Stabilized Zirconia (YSZ) thermal barrier coating controls the increase in engine temperature due to oxygen enrichment and avoids detonation. It was also found that the increase in oxygen concentration from 21% to 25% led to a rise in engine performance and control emissions such as hydrocarbons for about 10-15 ppm and carbon monoxide by 40%. It was also found that nitrogen oxide emission is maintained similarly to that of the diesel engine with the effect of alumina nanoparticle addition. It was also found that increasing the oxygen concentration reduces the OH concentration due to the lack of H atoms.

Keywords: Oxygen enrichment; Pressure swing adsorption; Thermal barrier coating; Emission; Nanoparticles.

1. INTRODUCTION

In the fast-growing phase of automobile industries, electric vehicles are on the verge of replacing traditional IC engines to overcome fuel costs and environmental emissions. However, the complete replacement of the IC engine is impossible due to its vast usage and the drawback of charging timing in electric vehicles. Much research is going on to improve the combustion behaviour of IC engines and reduce emissions. One such work is oxygen enrichment. If we increase the oxygen rate from 21% to 29%, there will be an increase in thermal efficiency and in-cylinder temperature and pressure by 8% and 4%, respectively (Zou *et al.* 2022).

Similarly, oxygen enrichment also decreases the BSFC, HC emission, CO emission, and smoke density by 12%, 40%, 55%, and 60%, respectively. The rise in temperature and pressure is due to the formation of a local stoichiometric mixture (Baskar and Senthilkumar, 2016). However, in the worst case, if we increase the oxygen concentration beyond 29%, deterioration is the end effect (Engin *et al.* 2020). Oxygen concentration also increases the heating rate and reduces fuel consumption. Another exciting result is that higher flame temperature is the end effect of higher oxygen enrichment (Wu *et al.* 2010). It is also clear that oxygen enrichment increases reaction kinetics and heat transfer characteristics (Yilmaz, 2019). An increase in oxygen concentration decreases the particle size diameter of soot particles and reduces smoke opacity, but there is an increase in tiny particles (Zhang *et al.* 2013). In the process of oxygen-enriched combustion, there is an increase in NOx emission by 4.9% and a considerable increase in vibration noises and exhaust gas temperature (Hazar *et al.* 2021). Retarded injection timing lowers the engine emission (Jain *et al.* 2023). Thin Film coating results in controlling the wear to a maximum extent so that coating on engine helps in increasing the life cycle of the engine.

Oxygen-enhanced and oxyfuel combustion effectively minimises material losses, increases productivity and efficiency, and reduces cost (Schluckner *et al.* 2018). Intake of oxygen enrichment also promotes the formation of OH, O, and H radicals, improving the early flame growth, specifically at the leading spark plug (Shi *et al.* 2020). Oxygenated biofuel usage also helps in improving emission standards, but it has some limitations. Membrane separation is the most suitable method of oxygen separation for small- to medium-scale applications. However, the oxygen thus obtained has a low purity range (Singh *et al.* 2024). Compared with the combustion process with air, membrane-based oxygen-enriched combustion exhibits energy savings of 35% and a net economic benefit of 29% (Lin *et al.* 2013). For high-purity oxygen requirements, going for pressure-swing adsorption is advisable. In zeolite, different grades are used for oxygen separation. When comparing natural and synthetic zeolite, we see that it provides oxygen enrichment in the range of 18.57% and 41.91%, respectively. In other cases, oxygen enrichment of a moderate oxygen mass fraction is needed to maintain stable propagation of ammonia through continuous rotating detonation (Ma *et al.* 2023). The addition of nanoparticles improves the engine performance and reduces nitrogen oxide emission (Shaisundaram *et al.* 2020).

The combustion equation is given as

$$C_xH_y + O_2 + N_2 = CO_2 + H_2O + NO + NO_2 + N_2$$

(Low NO_2 formation)

For oxygen-enriched combustion

$$C_xH_y + O_2 + N_2 = CO_2 + H_2O + NO_2 + N_2$$

(High NO_2 formation)

From the literature reviewed, it is evident that oxygen enrichment controls the CO and HC emissions but, there is an increase in NOx emission, and in-cylinder temperature and causes knocking. Thermal barrier coating controls the in-cylinder temperature and avoids knocking. Based on the literature it is found that 30ppm alumina nanoparticle is the optimum addition to the fuel results in controlling the increase of NOx emission to the optimum level *(*Bhan *et al.* 2024*)*. The major objective of this work is to overcome the drawbacks of oxygen enrichment in engines with the help of thermal barrier coating and nanoparticle addition. The combined effect of oxygen enrichment and alumina nanoparticles on the yttria-stabilized coated engine is an innovative approach that we have not seen before in any research work.

2. MATERIALS AND METHODOLOGY

Engine tests were conducted on the Kirloskar TV-1 engine, as shown in Fig. 1, the specifications of which are illustrated in Table 1. In this work, the experimental analysis of the diesel engine's exhaust emission at various levels of oxygen enrichment will be carried out. Engine tests were performed at different loading conditions in the thermal barrier-coated engine.

For thermal barrier coating, Yttria Stabilized Zirconia (YSZ) was chosen as the material for coating with a coating thickness of 50 microns. YSZ is preferred for coating because of its higher melting point, lower thermal conductivity, and high coefficient of thermal expansion. The coating is done using the plasma spray coating technique to uniformly coat the piston and inner sides of the cylinder and cylinder head.

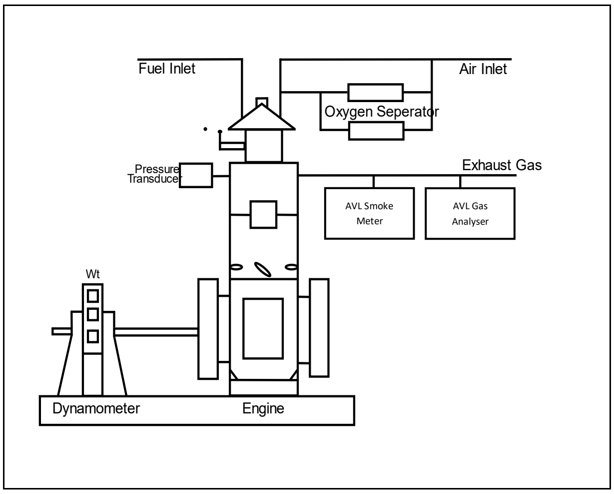

Fig. 1: Test engine setup

Table 1. Test engine specification

Model	Kirloskar TV-1
General details	Diesel engine test setup, Vertical cylinder
Cooling method	Water Cooled
Rated power	5.2 kW
Speed	1500 rpm
Number of cylinders	Single
Number of strokes	4
Compression ratio	17.5:1
Bore diameter	87.5 mm
Stroke length	110 mm
Ignition	Compression-Ignition

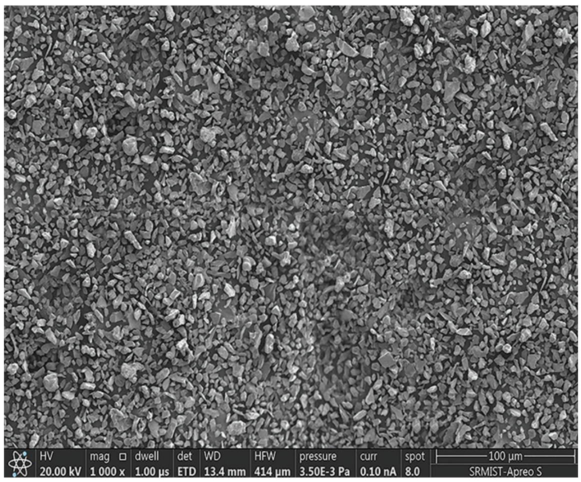

Fig. 2: SEM Image of alumina nanoparticles

Oxygen enrichment is done using a pressure swing adsorption (PSA) setup because of its ease of use and efficiency in oxygen supply to the engine. The PSA setup consists of two cylindrical columns as shown in Fig 1. as oxygen separator. These two columns are filled with zeolite 5A as an adsorbing material. When the air is allowed to pass through one of the columns, due to the adsorption property of zeolite, it only allows the oxygen molecule to pass through and block the nitrogen molecule. This nitrogen accumulation results in an increase in pressure. In the meantime, the second column is allowed to operate and the pressure in the first column is released, and vice versa.

To overcome this and ensure the continuous supply of oxygen to the engine, if the pressure inside the first cylinder is increased, it starts depressurized, and the flow will continue through the second line and vice versa. 30 ppm alumina nanoparticle additive is used to blend with the fuel to control the increase in nitrogen oxide emission of the engine. The alumina nanoparticles used in this research work are commercially procured from lab deals suppliers. To confirm the purity of alumina it is tested with a scanning electron microscope (SEM) and found that the equal dispersion of material is taking place which indicates that there are no impurities present in the powdered material. The SEM image of the alumina is illustrated in Fig. 2.

3. RESULT AND DISCUSSION

Engine emissions such as hydrocarbon (HC), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NO_x) were analyzed under various levels of oxygen enrichment in the yttria-stabilized zirconia-coated compression ignition engine. From the chemical analysis, it is found that the presence of excess oxygen results in the reduction of engine emissions such as CO and HC because with the presence of oxygen, complete combustion takes place, CO is converted to CO_2 and HC is reduced to hydrogen oxides. To test the engine emission at different loading conditions, the dynamometer coupled with the engine is loaded between 0 – 18 kg. The load factor is depicted in percentages with 0% for no load condition and 100% for full load condition.

3.1 HC Emission

Hydrocarbon emissions at varying load conditions for different concentrations of oxygen enrichment are shown in Fig. 3. With 25% oxygen enrichment, the HC particle emission will be reduced by 15 to 20 ppm. If the oxygen concentration increases beyond 25%, there are no considerable changes in emission. It is found that only a negligible amount of emission reduction is taking place. Considering the energy required for additional oxygen generation, 25% oxygen enrichment is optimal. Poor combustion increases the amount of unburned hydrocarbon emission. However, in this case, oxygen enrichment in the combustion chamber decreases HC emission by obtaining complete combustion, particularly at high loads.

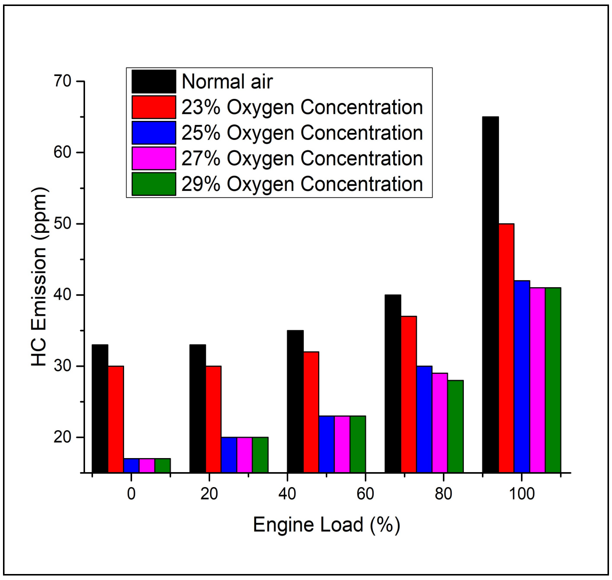

Fig. 3: Engine load (%) vs HC emission (ppm)

3.2 CO Emission

Fig. 4 shows the carbon monoxide emission at different loading conditions. With a 23% oxygen concentration, there is a 15% reduction in CO emission; when the oxygen level is increased to 25%, CO emission is reduced to 40%. Additional oxygen addition results in no significant changes in CO emission. The formation of carbon monoxide in engine emission is due to the incomplete combustion of fuel. Oxygen enrichment in engine combustion increases the combustion rate and minimizes CO emissions compared with conventional systems due to more complete combustion. From the result, it is found that 25% oxygen concentration is the optimized level of enrichment.

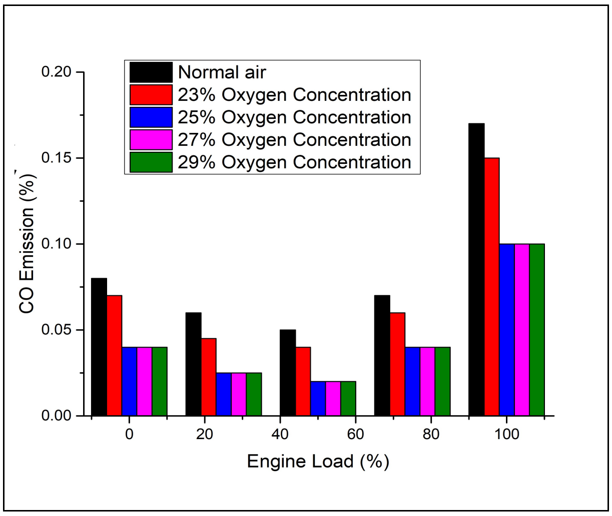

Fig. 4: Engine load (%) vs CO emission (%)

3.3 CO_2 Emission

Due to the presence of higher oxygen concentration, there is a considerable increase in Carbon dioxide emission in the engine due to complete combustion. This shows the promising reduction in greenhouse gases such as CO and HC. From the result, it is found that there is a considerable increase in CO_2 generation by about 3-5%. The CO_2 formation also increases the engine temperature and the Yttria stabilized zirconia coating acts against this and maintains the engine temperature at an optimum level.

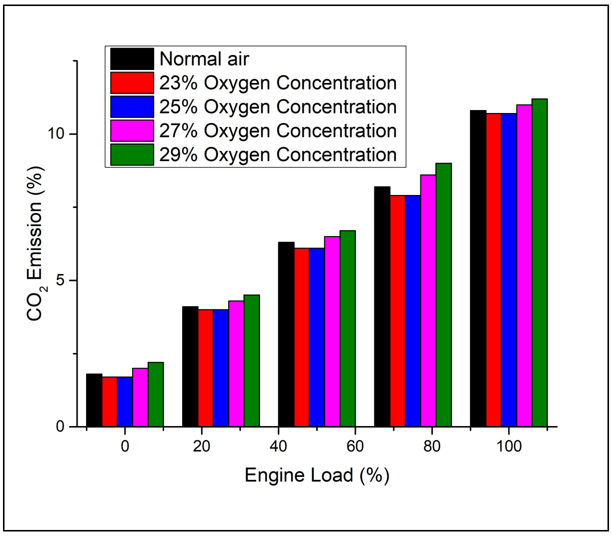

Fig. 5: Engine load (%) vs CO_2 emission (%)

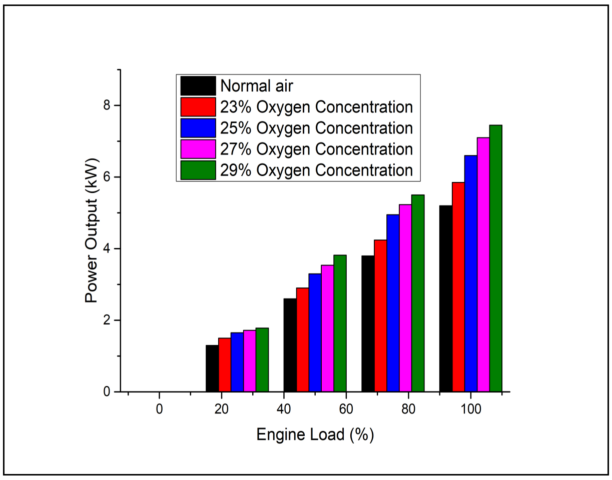

Fig. 6: Engine load (%) vs NO_x emission (ppm) without nanoparticle addition

3.4 NO_x Emission without the Addition of Alumina Nanoparticle

Nitrogen oxide emission at different oxygen concentrations is illustrated in Fig. 6. It was observed that the increase of oxygen concentration considerably increases the NO_x emission. The increase in oxygen concentration improves the NO_x emission by about 150 ppm. This increase in emission is the major concern in oxygen enrichment.

3.5 NO_x Emission with the addition of Alumina Nanoparticle

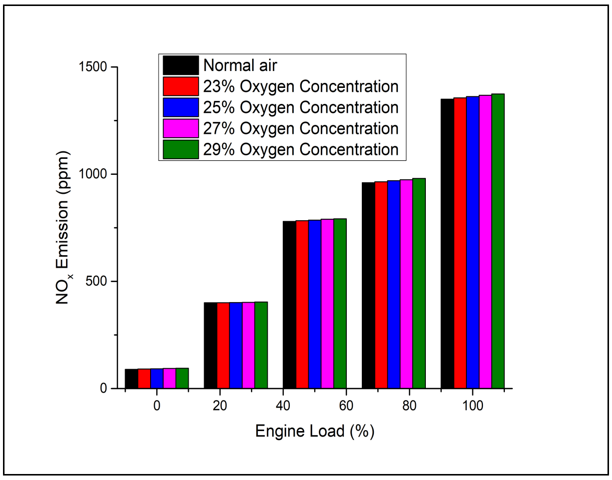

Fig. 7: Engine load (%) vs NO_x emission (ppm) with nanoparticle addition

Fig. 7 shows the nitrogen oxide emission at different oxygen concentrations along with the addition of alumina nanoparticles. From the figure, it is clear that in the presence of alumina nanoparticles, the NO_x emission so formed is nearly equivalent to that formed during direct diesel injection. From the result, it is clear that the addition of nanoparticles reduced the NO_x emission and the addition of oxygen improved the NO_x emission. Combining these two processes nullifies or 2-5% changes in emission and makes the oxygen enrichment more prominent.

4. CONCLUSION

From the analysis, it is found that with the oxygen enrichment, there is a considerable improvement in the emission characteristics of the engine. It was found that there was a control in emissions such as hydrocarbon and carbon monoxide increased by 10-15 ppm and 40%, respectively. It was also found that there was an increase in nitrogen oxide emission by 20% when there is an oxygen enrichment without the Nanoparticle addition and with the Alumina Nanoparticle addition the nitrogen oxide emission is increased by 2-5% which is optimal for operation considering the considerable decrease in CO & HC emission. Due to the complete combustion, CO_2 formation increases by 3-5%. From the result, it is concluded that 29% oxygen concentration provides a higher reduction of HC and CO emissions. However, considering the increase in NO_x emission and the energy needed for oxygen generation, it was found that 25% oxygen concentration is the optimum level for the enrichment of engine emission control.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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