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Full Length Article

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

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ABSTRACT

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

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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%.

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.

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.