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ORIGINAL ARTICLE

Experimental investigation on performance characteristics of a diesel engine using diesel-water emulsion with oxygen enriched air

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Abstract Diesel engines occupy a crucial position in automobile industry due to their high thermal efficiency and high power to weight ratio. However, they lag behind in controlling air polluting components coming out of the engine exhaust. Therefore, diesel consumption should be analyzed for future energy consumption and this can be primarily controlled by the petroleum fuel substitution techniques for existing diesel engines, which include biodiesel, alcohol-diesel emulsions and diesel water emulsions. Among them the diesel water emulsion is found to be most suitable fuel due to reduction in particulate matter and NOx emission, besides that it also improves the brake thermal efficiency. But the major problem associated with emulsions is the ignition delay, since this is responsible for the power and torque loss. A reduction in NOx emission was observed due to reduction in combustion chamber temperature as the water concentration increases. However the side effect of emulsified diesel is a reduction in power which can be compensated by oxygen enrichment. The present study investigates the effects of oxygen concentration on the performance characteristics of a diesel engine when the intake air is enriched to 27% of oxygen and fueled by 10% of water diesel emulsion. It was found that the brake thermal efficiency was enhanced, combustion characteristics improved and there is also a reduction in HC emissions.

1. Introduction

Diesel engines are always designed to operate with an excess air in the region of 15–40%, depending upon the application to find the necessary oxygen for 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 was that air-fuel ratio should be as close to stoichiometric as possible while operating at full load at the same time giving a better thermal efficiency and mean effective pressure.

The use of water in diesel fuel has numerous benefits. There are four primary methods of introducing water into the diesel engines: water injection into the cylinder using a separate injector, spraying water into the inlet air, intake manifold fumigation and water-diesel emulsions. Although all these methods lead to a reduction in NOx, the use of water-diesel emulsion

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was the most effective technique for the reduction in diesel particulates or smoke and it has been validated by the works of Mello et al. [1].

Diesel emulsion has an influence on reducing the peak flame temperature and hence reducing the NOx emissions. It has also been shown that addition of water may help to improve atomization and mixing, which is attributed to droplet micro-explosions as indicated by Murayama et al. [2]. The improved mixing is due to the increased vaporized fuel jet momentum, giving greater air entertainment into the fuel jet as explained by Kegl and Pehan [3].

Tree and Svensson [4] have seen that improved mixing also assists in the reduction in NOx emissions from the diffusive burning portion of the combustion cycle as well as reducing the carbon formation. This effect, combined with the chemical effect of the water results in an increased ignition delay as noted by Nazha et al. [5]. This in turn promotes an increase in the premixed portion of the combustion process, which decreases the diffusive burning and hence also contributes to the reduction in the NOx emissions and carbon formation as suggested by Subramanian [6].

There are also considerable data that suggest adding water to diesel fuel can reduce the particulate matter or smoke emissions as noted by Alahmer [7]. Liang et al. [8] find that, as the percentage of water in the emulsion increases, a larger amount of diesel is displaced by an equal amount of water, and this means that less diesel fuel is actually contained within each volume of the emulsion thereby decreasing the brake specific fuel consumption of the diesel engine.

Oxygen enriched air has been tried by the researchers over the years with the aim of reducing HC, CO, smoke, and particulate levels and improving the brake thermal efficiency in diesel engines. The major drawback of OEA technique is increasing NOx emissions; however, Virk et al. [9] conducted test on a single cylinder diesel engine to reduce the NOx emissions caused by the OEA and achieved it by low levels of enrichment along with retardation of injection timing. By using these optimized conditions, NOx levels were kept at the same value as the unenriched-air, while particulates and smoke emissions were reduced.

Donahue et al. [10] found that oxygen enhancement, whether it is from intake air enrichment or via oxygenated fuels, reduces particulate matter, the effectiveness depending on the local concentration of oxygen in the fuel plume. Oxygen-enriched intake air significantly reduces all the exhaust emissions except NOx; however, it improves the power density, lessens ignition delay, and allows the use of lower-grade fuels as reported by Poola et al. [11].

Cammarota et al. [12] and later Salzano et al. [15] proved that the OEA results in increased flame velocity and flame temperature, and this can lead to a flame propagation which is not deflagration but it is combustion induced rapid phase transition. It has also been noted by Rakopoulos et al. [13] that post treatment of the exhaust may be needed to control NOx levels when oxygen enriched air is used. Perez and Boehman [14] report that the oxygen enhancement helps to avoid a decrease in brake specific fuel consumption values at high altitude conditions and also maintains power output constant.

Lu et al. [16] studied the effect of lower oxygen concentration and found that 17% OEA causes an increase in soot and CO exhaust because of lower temperature in the later stages of combustion. Mohsen et al. [18] illustrate that oxygen enrichment is an effective way to reduce the knock tendency of pilot ignited natural gas- diesel engine at maximum load.

NOx emissions are generally increasing with OEA due to increased availability of atomic oxygen and also due to attainment of higher temperature during lean operation which enhances the kinetics for thermal NOx formation. This was clearly observed in the works of Jianxi et al. [17] and Baskar et al. [19].

The increase in NOx emissions is a key issue for further development and application of oxygen-enriched combustion in internal combustion engine. Earlier studies [16–22] have shown that oxygen-enriched combustion can greatly reduce particulate matter and soot significantly; however, NOx emissions will significantly increase if no special measure was applied. The harmful NOx emissions and PM purification methods of diesel engine contradict with each other, which makes it difficult to fully meet future stringent emission regulations.

In this research, the above two methods were combined in experimental tests to explore the coupling effects of oxygen enrichment and water contents of emulsified diesel fuel on NO emissions, cylinder pressure, heat release rate and brake thermal efficiency. A single cylinder, air cooled, four stroke cycle compression ignition engine was used for the above purpose.

2. Experimental method

To study the effect of oxygen concentration in the intake air and diesel-water emulsion as fuel for combustion, performance and emission characteristics a direct injection diesel engine is selected. A single cylinder constant speed diesel engine was run under variable load conditions. Experiments were conducted in four different phases. In the first phase the engine was run with neat diesel and 21% of atmospheric air and then in the second phase engine was fueled by 10% of water diesel emulsion. In the third phase the intake air was enriched with 27% of oxygen and neat diesel as fuel. Final phase consists of an engine was fueled by 10% diesel-water emulsion and 27% of oxygen enriched intake air in volume basis was used. The diesel-water emulsion prepared was obtained by adding 10% water (v/v) to the diesel fuel with the aid of surfactants that enabled the mixing of water and diesel.

2.1. Preparation of emulsion

Emulsification is the process of mixing the two immiscible phases by reducing the stress between these phases. It can be formed by the addition of water as the dispersed phase within a continuous diesel fuel phase leading to the formation of diesel water emulsion with the addition of surfactants. The addition of surfactants combines the different phases to form a single phase and its presence is very much essential in the formation of diesel-water emulsion. Surfactants' primary role was to lower the interfacial tension between the water phase and the diesel fuel phase. The secondary role was to stabilize the water droplet phase within the diesel fuel phase to avoid the coalescence mechanism of the water phase. Surface active material accumulates at the interfacial film between the water droplet phase and the diesel fuel continuous phase to stabilize the water droplet phase and thus, consequently stabilize the

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emulsion. In the current investigation, emulsion is formed by adding 10% (v/v) of water by volume. A high speed magnetic stirrer is shown in Fig. 1, having a speed of 2000 rpm is used in conjunction with a sonicator as shown in Fig. 2 to form a stable emulsion. Sonication is the process of employing sound energy to agitate particles in a mixture, for various purposes. Ultrasonic frequencies (>20 kHz) are used. 2% (v/v) surfactant (mixture of Span80 and Tween80) is added gradually to the diesel while it was being stirred in the magnetic stirrer. 10% (v/v) of distilled water was added drop wise to the mixture present in the magnetic stirrer. This mixture is stirred for a duration of 30 min. The mixture was then placed in a sonicator for one hour. The physiochemical property tests of diesel and 10% emulsified fuel sample were conducted using standard equipment.

Table 1 shows that the water content increases the density and viscosity of the emulsion with a corresponding decrease in calorific value. For the emulsion, calorific value decreases with increment in the water content as the water has no calorific value.

2.2. Experimental setup

The layout of the experimental setup used for investigation is shown in Fig. 3. The diesel engine was coupled to a Dynaspede eddy current dynamometer with 30 kW capacity. The fuel flow rate was obtained on the gravimetric basis using an electronic balance with an accuracy of 0.01 g. The air flow rate was obtained using a manometer setup. Horiba Mexa 548L exhaust gas analyzer was used to measure the HC and NOx levels in the exhaust by using Non-dispersive infrared principle. The Analyzer measures nitrogen oxides and total unburned hydrocarbon at a resolution of 1 ppm. The oxygen concentration was monitored by having Horiba analyzer at the exit side of the air box. The oxygen sensor in Horiba indicates the volume of oxygen present in the air with an accuracy of 0.1%. Sensors that were used in the experimental setup were proximity (inductive type), rotary encoder, thermocouple, pressure transducer and load cell. Proximity sensor was used for obtaining the top dead center position and speed measurement (rpm). Rotary encoder was used for crank angle measurements. The Kistler piezoelectric pressure transducer was employed for measuring in cylinder pressure (bar) at a mean value of 50 consecutive cycles. Thermocouple was used in two different locations to measure the ambient air temperature and the exhaust gas temperature. Load cell was used to monitor load provided by the dynamometer to the engine. AVL data acquisition system (AVL indicom compact) was used for acquiring and monitoring Real-time sensor data.

Figure 2 Sonicator setup.

Table 1 Physiochemical properties of the diesel and diesel water emulsion.

Fuel	Density [kg/m^2]	Calorific value [kJ/kg]	Viscosity [cSt]
Pure diesel	823.42	43,337	3.06
Diesel + 10% water	846.8	40,812	3.58

Figure 1 Magnetic stirrer setup.

2.2.1. Experimental procedure

Test conditions were designed to investigate the effect of oxygen concentration and emulsion on diesel engine performance and emission characteristics. Tests were carried out at different loadings starting from no load to the rated capacity of the

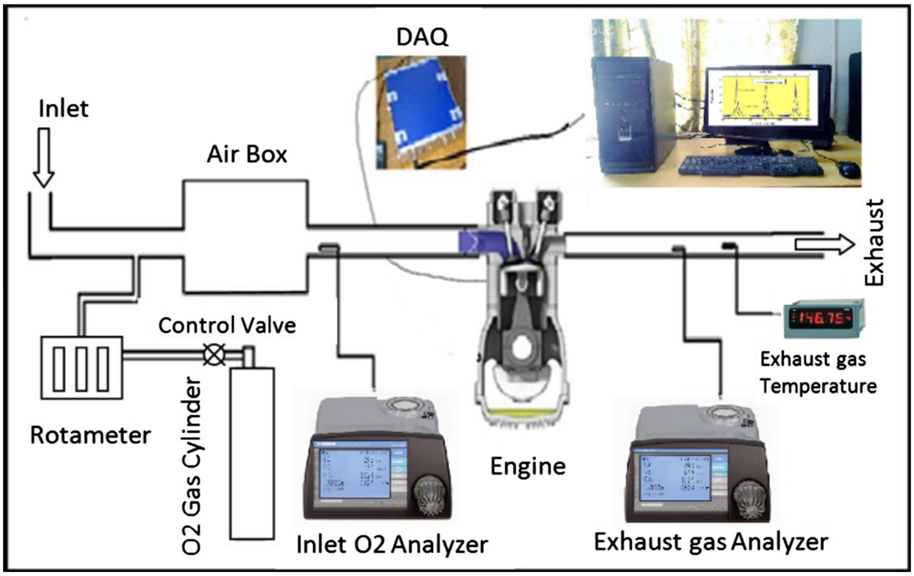

Figure 3 Layout of experimental setup.

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 initially running it for approximately 10 min at 1500 rpm and 50% of the load until the exhaust gas temperature reached 250 °C. Once these conditions are reached, the test engine was brought to the required test condition and then allowed for at least two minutes before collecting the data. Required oxygen concentration is achieved by mixing pure oxygen from a cylinder with atmospheric air in the air box.

2.2.2. Uncertainty analysis

The limiting factor associated with each measured parameter is estimated by comprehensive uncertainty analysis, based on the accuracy of the instrument used and the measured value. The uncertainty analysis of the measured parameters in the present study is summarized in Table 2.

2.2.3. Engine specification

A single vertical cylinder, air cooled, four stroke, compression ignition, and direct injection diesel engine having the specifications shown in Table 3 was used for conducting the experiments.

Table 2 Absolute error and uncertainty of measured parameters.

Measured parameters	Absolute error	Uncertainty (%)
Air flow at inlet	0.355 m^3/h	2.0
Rate of flow of diesel	8.37×10^{-3} kg/h	2.6
Rate of flow of oxygen	1.062×10^{-2} m^3/h	1.65
Engine speed	0.25 rev/s	1
Engine torque	0.6 N-m	2
NOx emission	2 ppm	2.35
HC emission	3 ppm	3.06
O_2 concentration	0.025%	0.66

Table 3 Specifications of the test engine.

Parameters	Specification
Displaced volume	662 cc
Stroke	110 mm
Bore	87.5 mm
Rated power	4.33 kW
Rated speed	1500 rpm
Compression ratio	17.5:1
Number of valves	2
Fuel injection	Direct injection
Injection timing	21 degree btdc
Injection pressure	230 bar

3. Results and discussion

The combustion, performance and emission characteristics of the engine fueled with baseline diesel, 10% of WDE, 27% of OEA and a combined use of 10% of WDE + 27% of the OEA under the part load and full conditions at a constant rated speed of 1500 rpm are reported below. Here in the above four phases are reported as neat diesel, WDE, OEA and WDE + OEA.

Fig. 4 shows the engine in-cylinder pressure for four phases under full load operating condition. The ignition timing was delayed by a degree in WDE phase and it gets advanced in OEA phase. The cylinder peak pressure increases slightly with OEA but at the same time with the use of WDE cylinder peak pressure reduces considerably. The maximum cylinder pressure achieved was 67.13 bar with OEA and it was reduced to 66.04 bar with WDE. However, with the combined use of WDE + OEA the peak cylinder pressure was 67.053 bar compared to 64.036 bar for neat diesel. However, these peak cylinder pressures occur ATDC 1 degree earlier for WDE + OEA and 1 degree later for WDE compared to neat diesel. Maximum pressure occurs earlier in OEA and WDE + OEA due

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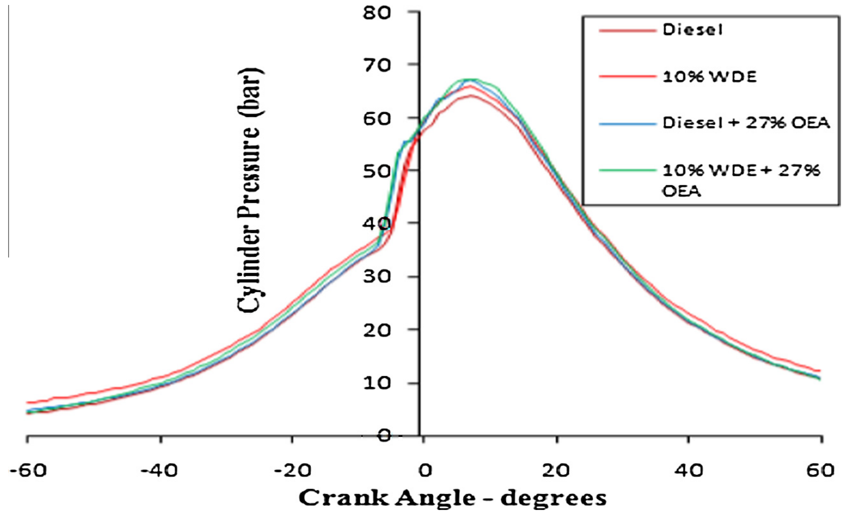

Figure 4 In-cylinder pressure variation with crank angle for four phases.

to reduction in delay period as shown in Fig. 8. This will greatly maximize the output torque and the efficiency of the engine operated with WDE + OEA.

Fig. 5 shows the variation of rate of pressure rise for four phases under full load operating conditions. Rate of pressure rise is the important factor which decides how smoothly the engine is running and how much noise is produced. It is observed that rate of pressure rise is very steep in the case of OEA as the steep slope indicates. In the case of WDE the slope angle is smaller. Its mainly due to the oxygen in the OEA promotes combustion and water in WDE inhibits the combustion. Maximum rate of pressure rise of 6.49 bar/CA is observed in OEA and a low of 5.7 bar/CA observed in WDE. Combined use of WDE + OEA ensures a moderate pressure rise.

Fig. 6 shows a heat release rate for four phases under the condition of full load. The heat release contains pre-mixed combustion and diffusion combustion. Under WDE operation, the in-cylinder heat release only contained a concentrated and intense exotherm process, since the ignition delay period extended significantly. Higher water emulsion ratio results in much longer ignition delay; therefore, the fuel and intake air mixture was more uniform since there was adequate time for the mixing process, and moisture within emulsified diesel can be also helpful to reduce the in-cylinder temperature. The maximum HRR was about 63.87 J/CA for WDE and a minimum of 42.95 J/CA for neat diesel. For OEA it is 45.26 J/CA and for WDE + OEA it is 49.45 J/CA. The maximum HRR for WDE occurs 3 degrees before TDC and it occurs 5 degrees before TDC for WDE + OEA and 6 degrees before TDC for OEA operation. If the HRR occurs very nearer to before TDC, there is a possibility of peak pressure occurring later in the expansion stroke, which will reduce the power output from the engine.

Fig. 7 shows a variation of cumulative heat release for four phases at full load operating condition. There is a delay in the start of combustion and an increase in the heat release rate in the premixed burn period as expected in the WDE operation and the maximum heat release is also higher for WDE. As it is also seen in Fig. 7 the cumulative heat release changes from negative to positive earlier in the case of OEA operation, which indicates a shorter delay period as it is shown in Fig. 8. There is an average of 6.4591 J/CA heat released in neat

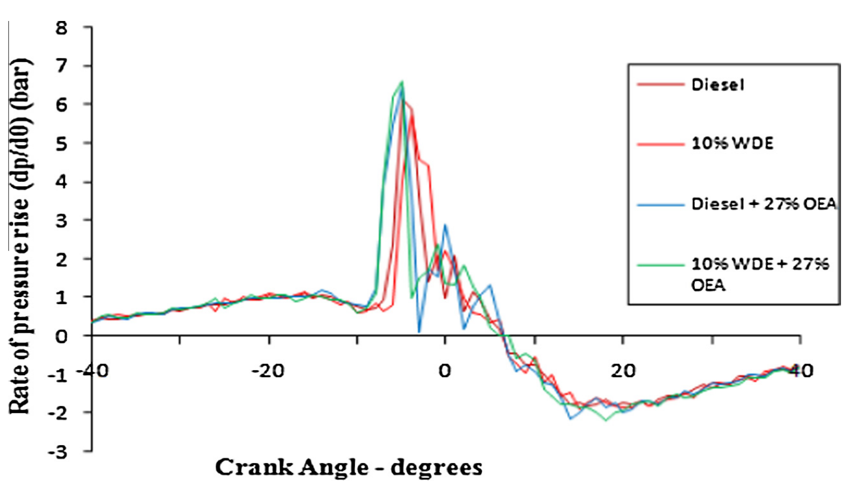

Figure 5 Rate of cylinder pressure rise variation with crank angle for four phases.

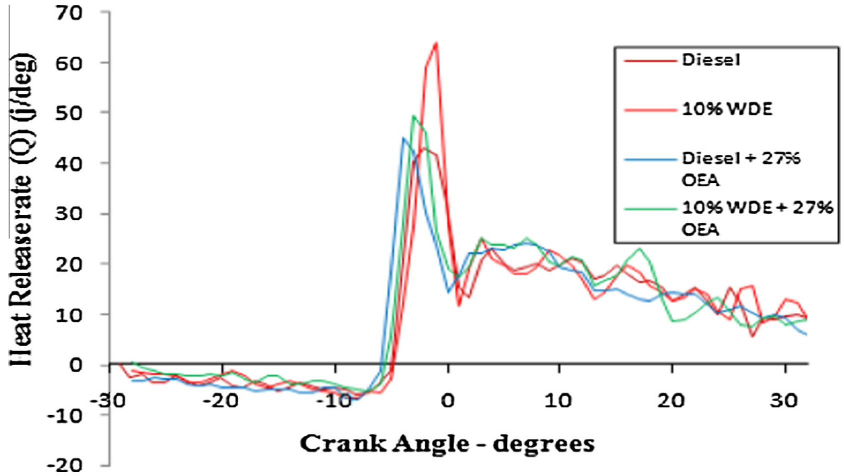

Figure 6 Heat release rate variation with crank angle for four phases.

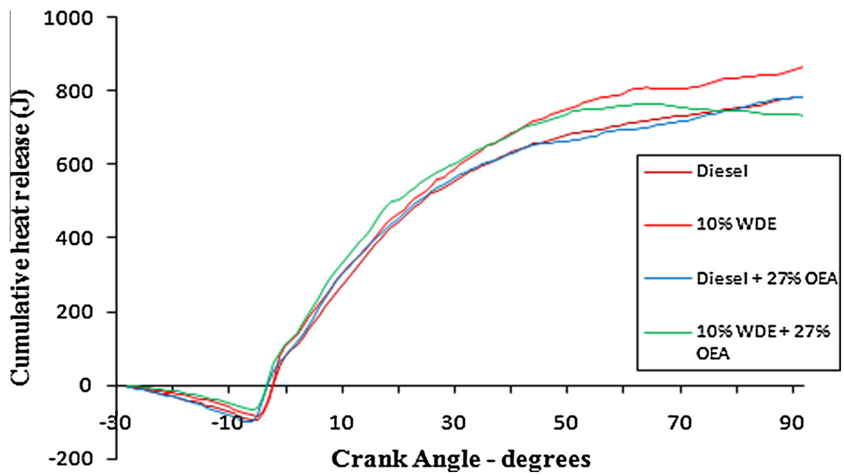

Figure 7 Cumulative heat release variation with crank angle for four phases.

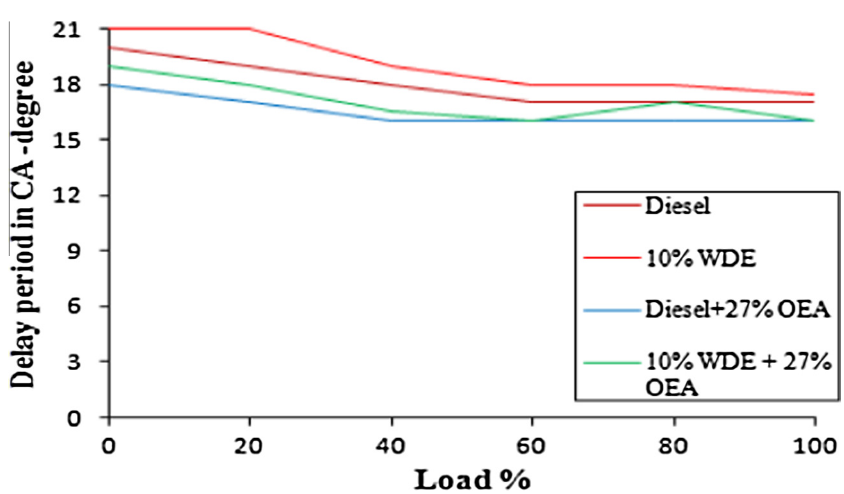

Figure 8 Delay period variations with load percentages for four phases.

diesel and it is increased to the maximum of 7.1703 J/CA for WDE. In the case of OEA the cumulative heat release is very similar to baseline diesel. However lowest value is achieved with combined use of WDE + OEA at the rate of 6.0589 J/CA.

Fig. 8 illustrates the delay period for different cases under part and full load conditions. It is clear from Fig. 8 that the oxygen doped intake air can advance in-cylinder ignition timing, accelerate combustion speed and slightly decrease the delay period under low-load and high-load conditions. Engine fueled with WDE can reduce the combustion temperature and prolong the ignition delay, the higher the water emulsification ratio longer the ignition delays [25]. The delay period can be controlled within a range of neat diesel by adjusting intake oxygen concentration and water emulsification ratio. The delay period was increased by 1 degree for the entire load range of WDE operation and it is decreased by 1 degree for WDE + OEA for all the loads compared to the neat diesel operation.

Wiebe function or 'S' curve describes the fraction of fuel that has been burned. This function is represented mathematically by Eq. (1).

$$X_b(\theta) = 1 - \exp\left[-a\left(\frac{\theta - \theta_i}{\theta_d}\right)^n\right] \quad (1)$$

$X_b(\theta)$ = Burn fraction as a function of crank angle; θ = Crank angle; θ_i = start of combustion; θ_d = Duration of heat release; n = Wiebe form factor; and a = Wiebe efficiency factor.

Typical values of $a = 5$ which corresponds to 99% burned mass in the function and $n = 3$ which corresponds to a high initial heat release rate are taken in this analysis. One of the most interesting observations of mass fraction burned profile is its half value that is crank angle 50 or CA50, which is the angle in which 50% of the total fuel has been burned. It is suggested that the optimum efficiency of the engine combustion is achieved if 50% energy conversion occurs at 8–10 crank angle degree after top dead center [20]. Fig. 9 illustrates this mass fraction burned profile for different cases under full load condition. It is observed that CA50 occurs at 13 degrees ATDC for WDE and 11 degrees for neat diesel. For OEA it is 10 degrees and for a combined use of WDE + OEA it is 9 degrees ATDC. Another important feature of the mass fraction burned curve is it shows how quickly the combustion takes place. It is seen from Fig. 9 that the MFB reaches unity much faster in WDE + OEA operation compared to other cases. At the same time WDE takes longer duration to reach unity.

Fig. 10 shows the variation of brake thermal efficiency for four phases under part load and full load condition. It is clear from Fig. 10 that there is an improvement in the BTE at higher loads with the WDE. In the case of the emulsion there is an increase in the ignition delay as it is seen in Fig. 8. This increases the premixed burn fraction. Thus the rate of combustion in the initial stages goes up.

Fig. 10 also indicates that with OEA there is an improvement in the BTE due to more complete combustion. Thus the combined use of WDE and OEA is advantageous in improving BTE. At the full load condition, the brake thermal efficiency with neat diesel is 30.5% and rises to 33.0% with the WDE. It is 32.0% with OEA but rises to 34.1% with combined use of WDE + OEA.

It is seen in Fig. 11 that there is about 5% to 10% increase in the HC emission level with the WDE as compared to neat diesel. The increase is primarily due to incomplete combustion caused due to a delay in the start of combustion and an increase in the heat release rate in the premixed burn period as seen in Fig. 6. When the oxygen concentration is increased, the HC level falls off significantly. An increase in the oxygen concentration to 27% reduces the HC level from 93 ppm to 27 ppm at full load. The combined use of WDE + OEA produces much lower HC levels than the neat diesel operation.

The NO emission in Fig. 12 shows that, when the engine fueled with water emulsified diesel, the in-cylinder temperature was reduced and the NO emission was inhibited. However, the NO emission increases quickly with oxygen-enriched intake, even if the engine fueled with water emulsion diesel, since oxygen enrichment in the combustion chamber is favorable to NO formation. The base NO emission was 1080 ppm when engine fueled with pure diesel and with 21% of oxygen concentration in inlet air at 100% load.

The NO emissions were 860 ppm when engine fueled with 10% emulsified diesel with 21% oxygen and 3040 ppm when engine fueled with pure diesel and with 27% oxygen in intake

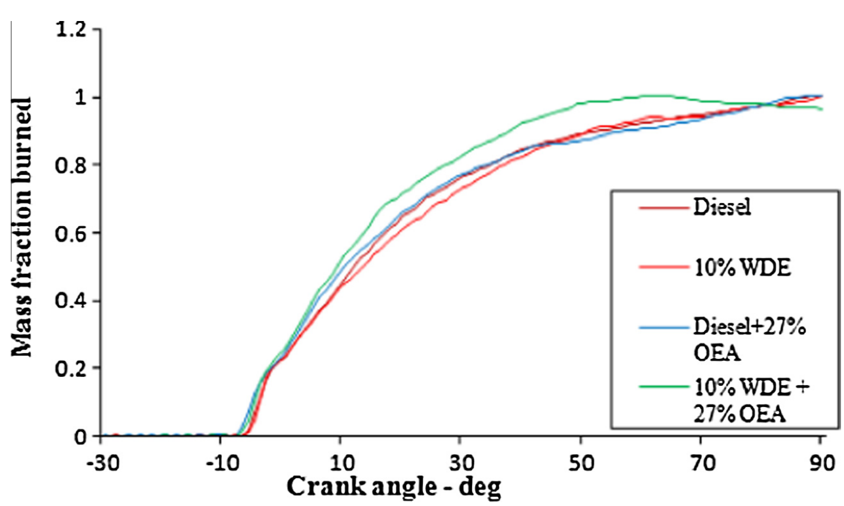

Figure 9 Mass fraction burned variation with crank angle for four phases.

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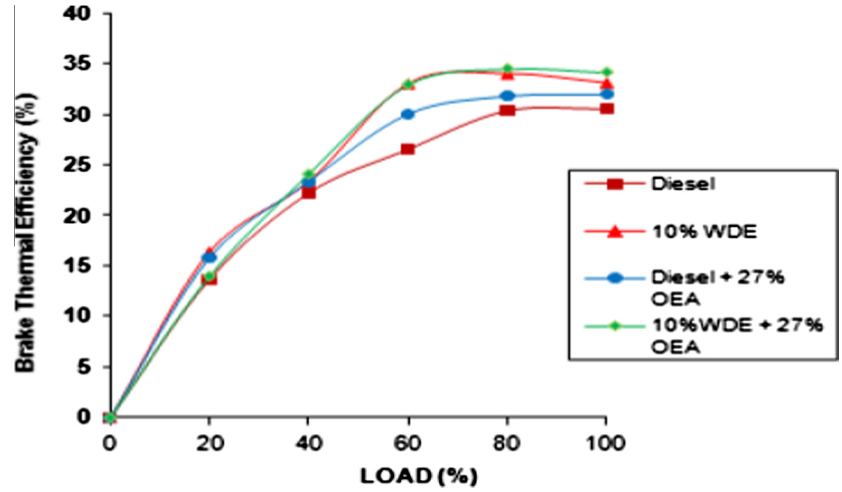

Figure 10 Brake thermal efficiency variation with load percentages for four phases.

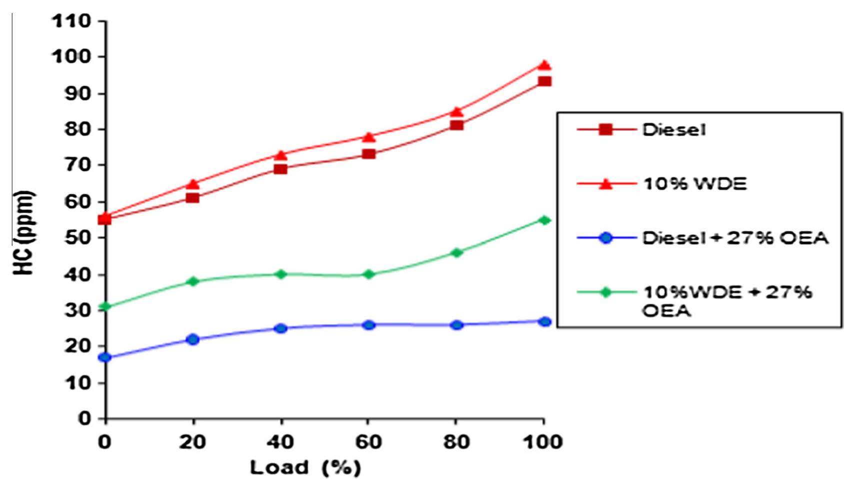

Figure 11 Hydrocarbon emission variation with load percentages for four phases.

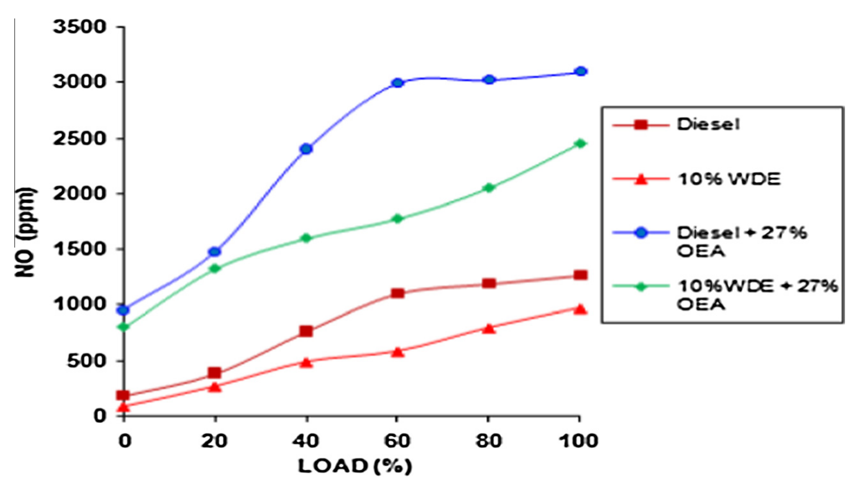

Figure 12 Nitrogen oxide emission variations with load percentages for four phases.

air. However, the NO values get reduced to 2450 ppm when engine fueled with 10% emulsified diesel and with 27% oxygen in intake air. From the comparison between these different operating conditions, it can be found that under the full-load condition of 100% load, the in-cylinder gas flow was more intense with the increase in fuel supply, and more moisture would enter the combustion chamber [24]. Therefore, the water emulsified diesel actually plays a more effective control of NO when intake oxygen concentration increases.

4. Conclusion

The noteworthy observations of experiments conducted using neat diesel, water-diesel emulsion, neat diesel with oxygen enrichment and water-diesel emulsion + oxygen enrichment are discussed below:

- The use of WDE improves the brake thermal efficiency over the entire load range; however, much higher efficiency is achieved by combining the use of 10% WDE and 27% OEA at higher loads.
- The peak pressure obtained inside the combustion chamber is maximum in the case of WDE + OEA when compared to diesel with OEA alone and neat diesel as fuel and also occurs at earlier crank angle.
- Even though the maximum heat release rate is obtained in WDE, the maximum value occurs earlier with WDE + OEA compared to WDE.
- The NO level is increased by using diesel with oxygen enriched air when compared to neat diesel as fuel. This increase in NO level brought down a considerable amount by using water-diesel emulsion with oxygen enriched air.
- Even though the hydrocarbon levels in the exhaust gas are minimum for neat diesel fuel, the use of diesel with OEA reduces the levels much lower in the exhaust. The use of water-diesel emulsion with oxygen enriched air slightly increases the hydrocarbon levels as compared to diesel with oxygen enrichment, but still levels obtained are much lower than those obtained for neat diesel.
- Delay period rises by about 4 CAD at full load with 10% WDE as compared to neat diesel operation. It is reduced by about 1 CAD when the oxygen level is enhanced by OEA.
- Change in delay period results in OEA + WDE faster combustion and WDE slower combustion.

On the whole it was concluded that using water-diesel emulsion and oxygen enriched air can lead to improvements in combustion, performance and emission characteristics of a diesel engine. The only drawback of the above combination is increased NO emissions; however, it can be controlled by optimized injection timing and after treatment devices.

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Further reading

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