Journal of Engineering Science and Technology
Vol. 7, No. 6 (2012) 711 - 721


# EXPERIMENTAL INVESTIGATIONS OF REAL TIME SECONDARY CO-INJECTION OF WATER – DIETHYL ETHER SOLUTION IN DI-DIESEL ENGINE FUELLED WITH PALM KERNEL METHYL ESTER

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**Abstract**

In this investigation tests were conducted on single cylinder diesel engine fuelled with neat diesel and biodiesel palm kernel methyl ester as a base line fuel with secondary injection of Water-DEE solution through the inlet manifold. A real time control systems consists of electronic unit pump that delivers 5% to 25% vol. Water-DEE solution through injector tip mounted nearer to the inlet manifold under a pressure of 3 kgf/cm$^2$. NOx emissions reduced to a level of 500 ppm with simultaneous reduction of soot especially for PKME. However for 15% vol. of Water-DEE injection the HC emissions are closely tallying with that of neat diesel. A global overview of the results has shown that the 15% Water-DEE solution is the optimal blend based on performance and emission characteristics.

Keywords: Water-DEE solution, PKME, Smoke, Nitrogen oxides.

## 1. Introduction

Biodiesels potentially reduce the dependence on petroleum diesel fuel and improve air quality. However it suffers from higher viscosity, cold starting problems and increased nitrogen oxides (NOx) emissions when compared with diesel oil. In this regard Oxygenation of diesel fuel offers the possibility of reducing particulate matter emissions significantly for diesel engines. There is considerable reduction of engine smoke when the oxygen content of diesel fuel is nearly about 38% by weight [1]. Catalytic after treatment is another method to reduce the emissions for biodiesel fuelled engines. Diesel oxidation catalytic converters are frequently used for after treatment of exhaust to reduce emissions NOx control catalysts, and plasma assisted catalysts to be implemented on diesel vehicles [2].

Blending jatropha methyl ester which is non edible oil in varying proportions with diesel fuel in 4 cylinder air cooled engine is studied by Elango and Senthilkumar [3]. Among the various blends the blends containing 20% Jatropha oil substantially reduced $CO_2$ with marginal decrease in thermal efficiency. But higher proportions of jatropha oil in diesel blend increased the specific fuel consumption with decrease in brake thermal efficiency.

Oxygenates significantly reduce hydrocarbon, carbon monoxide, and particulate emissions, but give a slight increase in NOx emissions. There is little or no increase in fuel consumption when an oxygenated diesel fuel is utilized. Reduced particulate matter emissions are a key benefit achieved through oxygenated diesel fuel use. In addition, it reduces unregulated aldehyde and ketone emissions. The magnitude of the particulate emissions reduction is directly proportional to the "oxygen" content of the ether oxygenate containing fuel. MTBE directly added to the diesel fuel to reduce the odorous emissions and improve the engine performance. 5% vol. MTBE blended in diesel fuel gives lower formaldehyde (HCHO) and an improved exhaust odor than with neat diesel fuel owing to good mixture formation. With higher percentages of MTBE blending in diesel fuel the positive effects of MTBE start deteriorating due to the formation of over lean mixtures [4]. Di methyl ether fuel was found to have excellent combustion properties that did not result in the discharge of any smoke over the entire operating range of the engine [5]. Controlled premixed combustion for DEE is used for achieving Ultra-low $NO_x$ emissions with zero particulate matter emissions. DME is injected into the premix chamber by means of the electronically controlled low pressure injection system, and then the mixture formation and combustion process were controlled with a control-valve set between the main chamber and the premix chamber. Controlled valve played an important role in controlling the pre-mixture formation and ignition timing [6].

Dual fuel technique is another technique used to reduce the smoke and emissions with improved engine performance. Methanol is injected along with stream of air through carburetor in to the inlet manifold of the engine by the bifurcated duct placed at the manifold inlet. Different mass flow rates of methanol were injected in to the engine by controlling the throttle valve openings and ignited by injecting neat Pongamia methyl ester at the end of the compression. Experimental results have shown that high speed combustion of methanol and higher latent heat helped in improving the combustion and reducing the emissions [7].

Water-emulsified diesel fuel technology reduces both nitrogen oxides ($NO_x$) and particulate matter (PM) simultaneously at relatively low cost compared to other pollution-reducing strategies. NOx is formed in the high-temperature regions at the diffusion flame and in the hot product gases, at a rate that increases exponentially with temperature [8, 9]. The water also acts as a temporary source of oxygen during this fuel-rich stage. Water lowers peak combustion temperatures which reduce formation of nitrogen oxides. The amount of NOx that is reduced is linearly correlated with the amount of water present in the emulsified fuel [10, 11]. A significant body of work was carried out at Brunel University in the late 1990s by Ladommatos et al. and Jacobs et al. [12-14]. To clarify the effect that dilution of the intake air by water vapor, carbon dioxide and combinations of these gases have on the combustion and emissions in a Diesel engine. Oil water oil emulsions resulted in lower exhaust gas temperatures and lower NOx, CO emission and smoke capacity but when compared to water oil emulsions O/W/O produced higher exhaust gas temperatures but lower CO and NOx emissions The W/O emulsions with 20% water content reduced NOx emissions by about 56.82%. The O/W/O emulsions with the same water content reduced NOx emissions by about 43.86% [15].

The RTWI system featured electronic unit pumps that delivered metered volumes of water to electronic unit injectors (EUI) modified to incorporate the water addition passages. Real time cycle-by-cycle control of water mass was used to mitigate soot formation during diesel combustion. With RTWI reduction of NOx is directly proportional to the load applied. But RTWI has limited for water injection and maximum water is injected is only 30% of the base line fuel [16]. Biodiesel blended with DEE/Water emulsion shows that there is an improvement in brake thermal efficiency, higher reduction of $NO_x$ than blending biodiesel with DEE. But however biodiesel blended with DEE has shown much reduction of HC than with DEE/Water emulsion [17]. The purpose of this investigation is to study the effect of water-DEE emulsion with dual injection of diesel and biodiesel palm kernel methyl ester on $NO_x$ and HC emissions with controlled injection of Water-DEE solution and deciding the optimum ratio of the emulsion with respect to the base line fuel Diesel and PKME.

## 2. Engine Tests - Experimental Methodology

A four stroke, direct injection, naturally aspirated single cylinder diesel engine is employed for the present study whose details are given in Table 1. Figures 1 and 2 show the diesel engine test rig with water-DEE injection equipment and the Schematic Diagram of Experimental Set-up respectively.

The maximum solubility of DEE in water is 50 ml/lit and the percentage of DEE blended in water is around 5% vol./wt. basis. This Water-DEE solution is injected at the suction end at a pressure of 3 kgf/cm$^2$. The injection is controlled electronically by a controlled injection pump designed with suitable hardware and it is timed to inject after full suction valve opening. This Water-DEE solution is injected at 5%, 10%, 15%, 20%, and 25% volume basis calculated against the diesel consumption as reference.

The tests are conducted at the rated speed of 1500 rpm at different loads equals to 0 kg, 10 kg, 20 kg, 30 kg, and 40 kg in the spring balance readings. The engine was run with neat diesel and then with neat palm kernel methyl ester while the secondary injection of Water-DEE solution is injected at the suction end with different mass flow as indicated above. Engine tests were run on the same engine and on same day for both diesel and PKME for each load, in order to have almost the same atmospheric conditions. The cooling water temperature was maintained constant (60°C to 65°C). All observations recorded were replicated thrice to get a reasonable value. The performance characteristics of the engine are evaluated in terms of brake thermal efficiency, brake specific fuel consumption (BSFC), and emission characteristics in terms of smoke. The experimental data generated are documented and presented here using appropriate graphs.

These tests are aimed at optimizing the injection of percentage of Water-DEE solution for long-term engine operation. In each experiment, engine parameters related to thermal performance of the engine such as fuel consumption and applied load are measured. In addition to that, the engine emission parameters such as carbon monoxide (CO), carbon dioxide ($CO_2$), oxygen ($O_2$) Nitric oxide (NOx) are also measured. The results are compared with the characteristics of 100% Neat Diesel oil fuelled engines as well Palm Kernel Methyl ester whose specifications are given in Table 2.

**Table 1. Engine Specifications.**

| | |
|---|---|
| **Type** | Four strokes, Single cylinder compression ignition engine |
| **Make** | Kirloskar AV-1 |
| **Rated power** | 3.7 kW |
| **Bore Stroke** | 80 mm×110 mm |
| **Compression ratio** | 16.5:1 |
| **No of Cylinders** | 1 |
| **Cylinder Capacity** | 624 cc |
| **Dynamometer** | Electrical AC Dynamometer |
| **Pressure, piezo sensor** | 2000 psi |
| **Injection pressure** | 210 bar |

**Table 2. Properties of Bio-Diesel (Palm Kernel Methyl Ester).**

| Property | Method | Units | Specification |
|---|---|---|---|
| **Cetane Number** | EN 590 | | 51 |
| **Copper Strip Corrosion(3H, 50°C)** | EN ISO 2160 | Degree of corrosion | 1.0 |
| **Density; 15°C** | EN ISO 3675 | $kg/m^3$ | 860-900 |
| **Ester Content** | EN14103 | %(mol/mol) | 96.5 |
| **Flash Point** | EN ISO 3679 | 0°C | 170 |
| **Gross Calorific Value** | | kJ/kg | 38,800 |
| **Iodine value** | EN14111 | $gI_2/100$ g | 120 |
| **Pour Point** | ISO 3016 | 0°C | -3 |
| **Ram's bottom carbon residue wt%** | EN ISO10370 | %(mol/mol) | 0.36 |
| **Total Glycerin** | EN14105 | %(mol/mol) | 0.25 |
| **Viscosity; 40°C** | EN ISO 3104 | $Mm^2/S$ | 3.5-5.0 |


**Fig. 1. Diesel Engine Test Rig with Water-DEE Injection Equipment.**

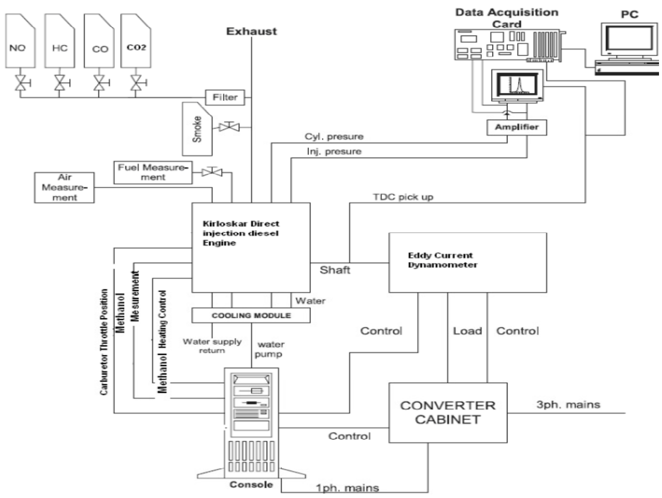


**Fig. 2. Schematic Diagram of Experimental Set-up.**

## 3. Results and Discussion

The Biodiesel PKME has higher Cetane number when compared to the diesel because of which the ignition delay of PKME is less than diesel and PKME has steep rise in pressure and the start of combustion is advanced. The water-DEE solution delayed the combustion and peak pressure occurrence as can be seen from the Figs. 3 and 4.

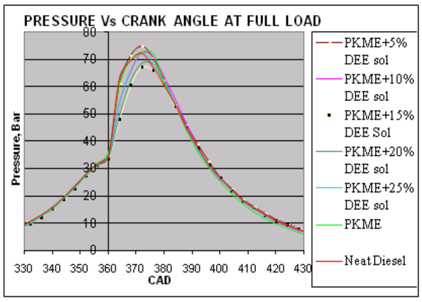


**Fig. 3. Variation of Pressure vs. Crank Angle at Full Load.**

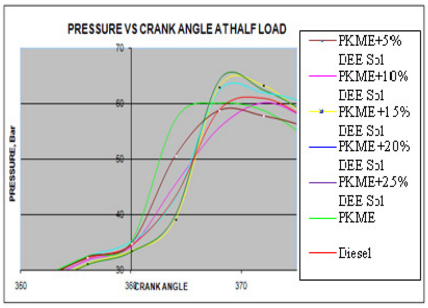


**Fig. 4. Variation of Pressure vs. Crank Angle at Half Load.**

The specific fuel consumption has increased with the implementation of saturated water-DEE solution injection thereby increasing the equivalence ratio at full load. This may be because of the dilution created by the presence of saturated water-DEE solution which obviously reduces the burning rate of the bio diesel Palm kernel methyl ester. Figures 5 and 6 portray the specific fuel consumption variation with load higher flow rates of water-DEE solution resulted increase in SFC when compared to 5% vol. Water-DEE solution.

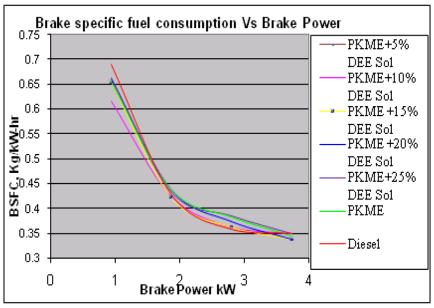


**Fig. 5. Variation of Brake Specific Fuel Consumption vs. Brake Power.**

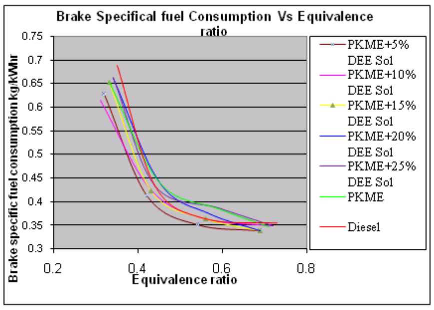


**Fig. 6. Variation of Brake Specific Fuel Consumption vs. Equivalence Ratio.**

Variation of brake thermal efficiency for different percentages of Water-DEE solution with PKME at different loads is shown in Fig. 7. BTE is increased from 22% to 24% for PKME when 15% vol. Water-DEE solution is injected. Presence of DEE creates micro explosions causing better air entrainment since DEE is first to evaporate than water due to its lower boiling point and higher evaporation rate [18]. But diesel is having higher BTE when compared to PKME since diesel is having higher calorific value. Higher percentages of water-DEE solution beyond 25% volume should not be tried due to crank case oil contamination.

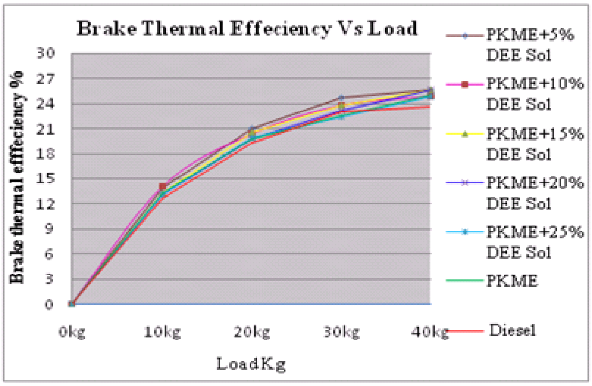


**Fig. 7. Variation of Brake Thermal Efficiency vs. Load.**

At full load HC emission in the exhaust has decreased with the increased volume of water-DEE solution. At full load there is a straight decrease of 30 ppm with increase of water-DEE solution from 5% to 25% as depicted in the Fig. 8. The rise in HC is Maximum to the tune of 110 ppm at 15% vol. Water-DEE solution at Zero load on the engine this is due to the charge dilution because of low combustion temperatures. Therefore no load running of the engine is not suggested. Neat biodiesel PKME operation at all loads emitted least amounts of HC when compared to all aspects of duel fuel operation. Palm methyl ester has proven history of HC, CO & smoke reduction in the exhaust gas.

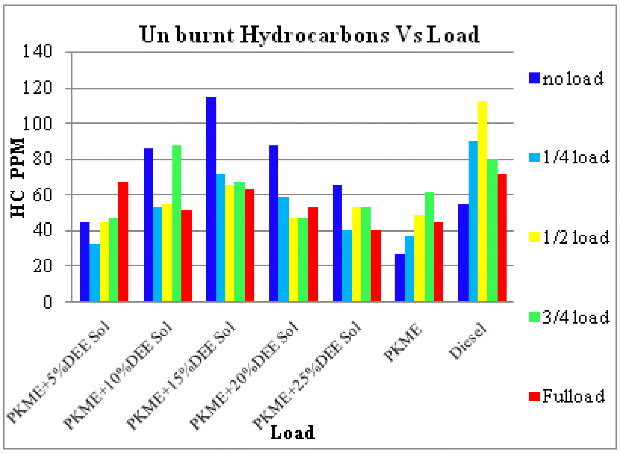


**Fig. 8. Variation of Unburnt Hydrocarbons vs. Load.**

There is no trade off observed between the HC emission and the NO emission. NO emissions decreased from 1400 ppm to 770 ppm for full load operation when water-DEE solution injection is increased from 5% to 25% as shown in the Fig. 9. This is due to the cooler combustion and better vaporization of fuel in the air entrainment caused due to the micro explosions of DEE. Neat PKME and diesel has emitted maximum ‘NO’ in the exhaust gas and this is also true to the data obtained in previous research done on biodiesel application in diesel engines [19].

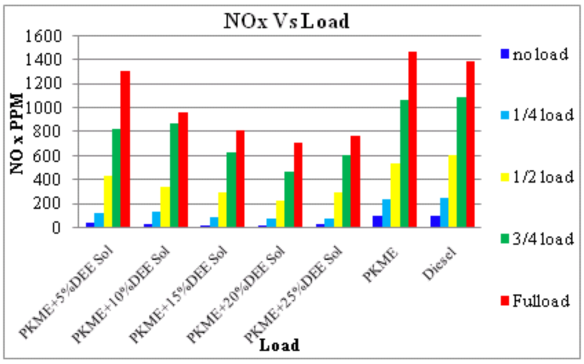


**Fig. 9. Variation of NOx vs. Load.**

CO and smoke has decreased marginally for the flow rate of 15% vol. Water-DEE solution as shown in Fig. 10. 'CO' emission with 15% vol. Water-DEE solution injection is creating parity with the neat diesel operation at higher loads as shown in Fig. 10. Certain amount of sacrifice is to be made in the area of CO emission, while battling with the reduction of 'NO' emission.

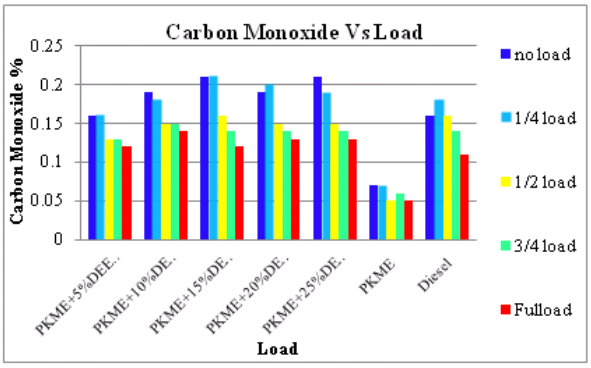


**Fig. 10. Variation of Carbon Monoxide vs. Load.**

There is no appreciable change in $CO_2$ emission with respect to the duel fuel operation as shown in Fig. 11. Flow rate of 15% vol. Water-DEE solution is approximately tallying with the diesel fuel operation in the area of $CO_2$ emission.

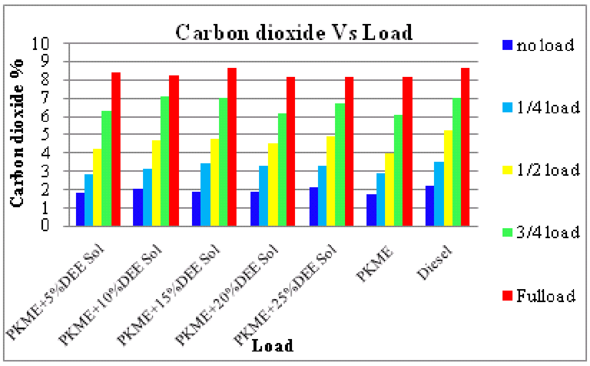


**Fig. 11. Variation of Carbon Dioxide vs. Load.**

Free Oxygen in the exhaust gas in the case of 15% vol. Water-DEE solution injection is in reasonable comparison with the neat diesel operation. Free air (Lambda) in the exhaust gas is almost same with or without duel fuel operation as shown in Fig. 12.

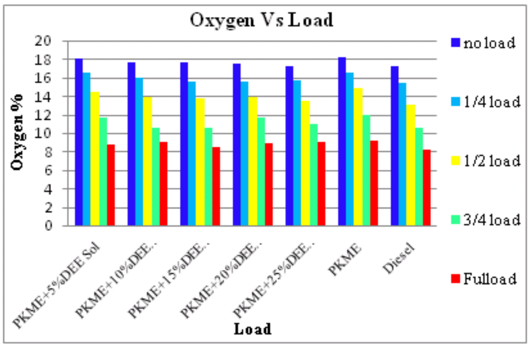


**Fig. 12. Variation of Oxygen vs. Load.**

The variation of exhaust gas temperature for different percentages of water-DEE solution for all loads is shown in Fig. 13. EGT for neat PKME is higher than that of neat diesel this may be attributed to the heavier molecules of PKME leads to continuous burning during exhaust which causes higher exhaust gas temperature [20]. Water-DEE solution has certainly reduced the exhaust gas temperature up to 15% vol. of injection but for higher percentages of water-DEE solution the positive effects of secondary injection starts deteriorating. Water – DEE injection reduced the combustion temperatures due to the absorption of latent heat of vaporization leading to cooler combustion.

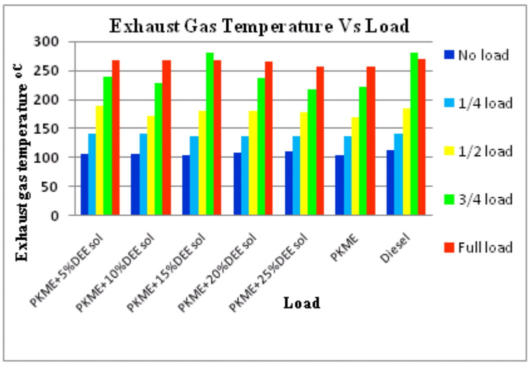


**Fig. 13. Variation of Exhaust Gas Temperature vs. Load.**

The variation of smoke levels for different volumes of Water-DEE solution is shown in Fig. 14. Smoke levels starts decreasing from 5% to 15% vol. of Water-DEE solution for full load but there are some fluctuations in some parts especially at higher loads, for more than 15% vol. Water-DEE solution due to erratic combustion. There is a trade-off between oxygen content and latent heat for DEE in water. In the other words, its oxygen content leads to smoke reduction [21] and its high LHV decreases the combustion temperature and consequently UHC increases due to wall quenching effects and finally smoke will arise**.** Smoke levels for 15% vol. Water-DEE solution is lesser than that of diesel for all loads but smoke levels of neat PKME is lower than that of 15% vol. Water-DEE solution along with PKME this is due to the fact PKME have higher combustion temperatures than PKME with water-DEE solution.

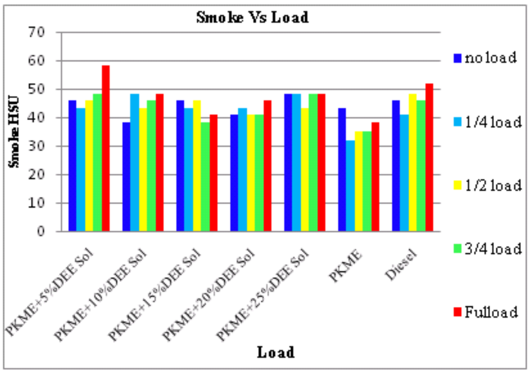


**Fig. 14. Variation of Smoke vs. Load.**

## 4. Conclusions

Some concluding observations from the investigation are given below

- The peak pressure values also reduced with respect to the quantity of saturated Water-DEE solution injected.
- The constituent DEE combustion in the saturated water-DEE solution may also produce micro explosions in the combustion zone to pave way for better diffused combustion and air entrainment.
- There is straight increase in thermal efficiency to the tune of 2% at full load Operation with the injection of 15% vol. Water-DEE solution along with bio-diesel (Palm Kernel Methyl ester).
- The crank case oil dilution started after the flow rate of 20% vol. Water-DEE solution injection.
- At Full load running of the engine the Specific fuel consumption for the flow rate of 15% vol. Water-DEE solution coincided with that of injection, indicating that the mass flow rate of 5% vol. Water-DEE solution (thresh hold percentage) in the duel fuel operation is beneficial in view of other advantages from the exhaust pollution angle especially in the case on ‘NO’ emission.
- Exhaust gas temperatures at all loads in the case of 15% vol. Water-DEE solution injection are almost equal to the temperatures emitted during neat diesel operation.
- There is a straight reduction of approximately 500 ppm in NO level when the flow rate of saturated water-DEE solution is increased from 5% vol. to 15% vol. Water-DEE solution.
- The emission of HC with the injection of saturated 15% vol. Water-DEE solution is closely tallying and proximate to the neat diesel operation.

- 'CO' emission with the flow rate of 15% vol. Water-DEE solution injection is creating parity with the neat diesel operation at higher loads.

**Acknowledgment**

The author thanks Prof. B.V. Appa Rao, Department of Marine Engineering, Andhra University, and Visakhapatnam for the unstinted support in guiding my research in this field.

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