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Effect of Oxygenated DEE Additive to Ethanol and Diesel Blend in the Context of Performance and Emissions Characteristics of CI Engine

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Abstract

An experimental investigation has been carried out to evaluate the effects of oxygenated cetane improver Diethyl ether (DEE) as additive to optimum ethanol-diesel blend on the performance and emission characteristics of a direct injection diesel engine. The DEE with 5%, 8%, 10% and 15% (by volume) are blended into optimum 10% ethanol-diesel blend. The engine tests are carried out at 25%, 50%, 75% and 100% of full load for all test fuels. The laboratory fuel tests show that the DEE is completely miscible with diesel and ethanol in any proportion. The concentration of DEE in the DEE-ethanol-diesel blends increases the oxygen content, cetane number and reduces the density, kinematic viscosity and calorific value. The experimental results of DEE-ethanol-diesel blends at full load condition show that the BTE of DE8E10D is improved by 15%; the smoke and NOx emissions of DE15E10D are reduced by 6.25% and 36% respectively; while the CO and HC emissions are increased by 43% and 42% respectively as compared to neat diesel. It has reduced the trade-off between smoke and NOx. The optimum performance blend ratio found is DE15E10D without any modifications in the engine.

Keywords: DEE, Ethanol, Diesel, Performance, Emissions

INTRODUCTION

The overwhelming demand for diesel engines in transportation, industrial and agricultural sectors are putting an additional pressure on existing conventional hydrocarbon reserves. These are already producing more hazardous emissions than its prescribed limits particularly high concentration of NOx and particulate emissions. Simultaneous reduction in NOx emission and particulate matter is quite difficult due to trade off between PM and NOx which is often accompanied by fuel consumption penalty [1, 2]. Although, it is more difficult for diesel engines to meet stringent emission norms by the use of conventional fuel such as petroleum diesel and biodiesel as a neat fuel through engine design or control parameters alone. However, the depletion of hydrocarbon reserves, the escalation of conventional fuel prices and the stringent emission norms incites the researchers to look for an alternative fuel which can replace or supplement the fossil fuels. So we need some kind of alternative source which must be renewable, easily available, cost effective and most importantly environmental friendly [3,4].

Many researchers worked on this issue and found an oxygenated alternate fuel. The oxygenated bio-fuels made from agricultural products offer benefits in terms of exhaust emissions and reduce the world's dependence on oil imports. Among all oxygenates, a worldwide trend towards the application of mostly biodiesel and alcohols have been observed for the last two decades [5-6]. In spark-ignition engines the alcohol fuels can be substitute for gasoline, while in compression ignition engines the biodiesel, green diesel, DEE, DME and hydrogen are more suitable [7].

Among various alternative fuels, ethanol is promising oxygenated alternative fuel. It is a renewable, bio-based and highly oxygenated fuel, thus providing the potential to reduce exhaust emissions in CI engines and demonstrates promising future fuel for SI engines due to its high octane quality. Though, there are many obstacles in the use of ethanol in CI engines such as very low cetane number, poor ignition characteristics and limited solubility in diesel fuel. The phase separation and water tolerance in ethanol-diesel blend fuels are crucial problems. The dynamic viscosity of ethanol is much lower than diesel fuel. Therefore, the lubricity is a potential concern of ethanol-diesel blend fuels [8]. Stability of the blend is dependent on the water content of the blend, ambient temperature, hydrocarbon composition and wax content of the diesel fuel. Ethanol has limited solubility in diesel fuel. Addition of less than 10% ethanol to diesel fuel makes the blend almost stable. Moreover, a blend of 10% ethanol to diesel for less than 10 °C is unstable. These problems of ethanol-diesel blend can be solved by introducing a co-solver or an emulsifier to the blend [9]. Diethyl ether (DEE) seems to be one of the promising candidates to meet these requirements. The DEE is completely soluble in diesel and in ethanol. The addition of DEE to ethanol-diesel blend work as a co-solvent and makes ethanol compatible with diesel [10-11].

In this research work the optimum 10% ethanol-diesel blend is selected and DEE is added in various proportions to investigate the performance and emissions of DEE-ethanol-diesel blends. Diethyl Ether is a promising alternative oxygenated renewable bio-base resource fuel. DEE has several favorable properties such as high cetane number, low auto ignition temperature, high oxygen content, high miscibility with diesel fuel, broad flammability limits and reasonable energy density for on-board storage [12]. At ambient conditions, it is in liquid form, which makes it attractive fuel for handling and infrastructure requirements. DEE is an organic compound in the ether class also known as ethyl ether, sulfuric ether, simply ether, or ethoxyethane, It is a common laboratory solvent often used for liquid-liquid extractions (generally called solvent extractions) [13]. It is expressed by its chemical formula CH_3CH_2-O-CH_2CH_3, consisting of two ethyl groups bonded to a central oxygen atom.

EXPERIMENTAL FUELS AND ITS PROPERTIES

The experimental fuels such as diesel and ethanol (analysis grade, 99.5% purity) are purchased from local commercial representative and the DEE (purity ≥ 99.5%, EMPARTA analytical grade) is procured from local commercial representative of MERCK. The DEE and ethanol are blended with conventional diesel fuel in different proportions by manual mixing at room temperature. In this work, 5%, 8%, 10% and 15% DEE (by volume) are blended as additive into 10% Ethanol-Diesel selected optimum blend. These blends are denoted as DE5E10D, DE8E10D, DE10E10D and DE15E10D respectively. Also neat diesel, neat ethanol, neat DEE and 10% ethanol-diesel blend are denoted as D100, E100, DE100 and E10D respectively.

The fuel tests are carried in laboratory for different physicochemical properties of blends. The test results reveal that DEE is completely miscible with diesel and ethanol fuel. The concentration of DEE in the diesel-ethanol blends increases the oxygen content, cetane number and reduces the density, kinematic viscosity and calorific value. It demonstrates that the desirable physical properties of diesel fuel are retained with cleaner burning capability of DEE and ethanol. The lubricity reduction is one of the main reasons for keeping less than 15% DEE in the blends. The physicochemical properties of different DEE-ethanol-diesel blends are shown in Table 1.

Table 1. Physicochemical properties of DEE-ethanol-diesel blends

Fuel blend	Kinematic Viscosity @ 40º C (cSt)	Density @ 20º C (kg/m³)	Higher Calorific Value (MJ/kg)	Cetane Number	Oxygen Content (wt. %)
D100	2.45	820	45.6	52	0
E100	1.19	789	29.7	8	34.7
DE100	0.23	713	43.00	>125	21.6
E10D	2.36	812.5	43.22	47.6	3.47
DE2E10D	2.12	812	43.23	49.06	3.90
DE5E10D	1.97	809	42.98	51.25	4.55
DE8E10D	1.71	807	42.01	53.44	5.20
DE10E10D	1.68	804	41.66	54.9	5.63
DE15E10D	1.58	801	40.73	58.55	6.71

ENGINE TEST RIG

At researchers place the engine testing facilities with suitable instrumentation are developed for single cylinder, four stroke cycle, naturally aspirated, direct injection diesel engine to measure performance, emission and combustion parameters. The developed engine test rig includes suitable dynamometer, speed and load measurement systems along with its fine control, innovative cooling system to maintain uniform engine temperature, gravimetric fuel consumption measurement to reduce the effect of density variation, air flow measurement system, high speed data collection and combustion analysis system including cylinder pressure sensor, crank angle encoder. To measure the exhaust emissions, the compatible exhaust system is developed for five gas analyzer (AVL Digas 444) and smoke meter (AVL 437). The data analysis is made through data acquisition card and data processing software. The specifications of test engine are given in Table 2. The schematic block diagram of engine test rig is shown in Figure 1.

Table 2. Specifications of test engine

Model	Kirloskar, TV1 model
Engine type	Single cylinder, 4-stroke, water-cooled, DI
Bore x Stroke	87.5 mm x 110 mm
Aspiration	Naturally aspirated
Displacement	0.661 litre
Compression ratio	18:1
Rated power	3.7 kW
Rated speed	1500 rpm
Fuel injection system	Single barrel F.I. pump, inline fuel injector
Fuel injection timing	23 deg. BTDC (static)
Inj. opening pressure	20.5 MPa

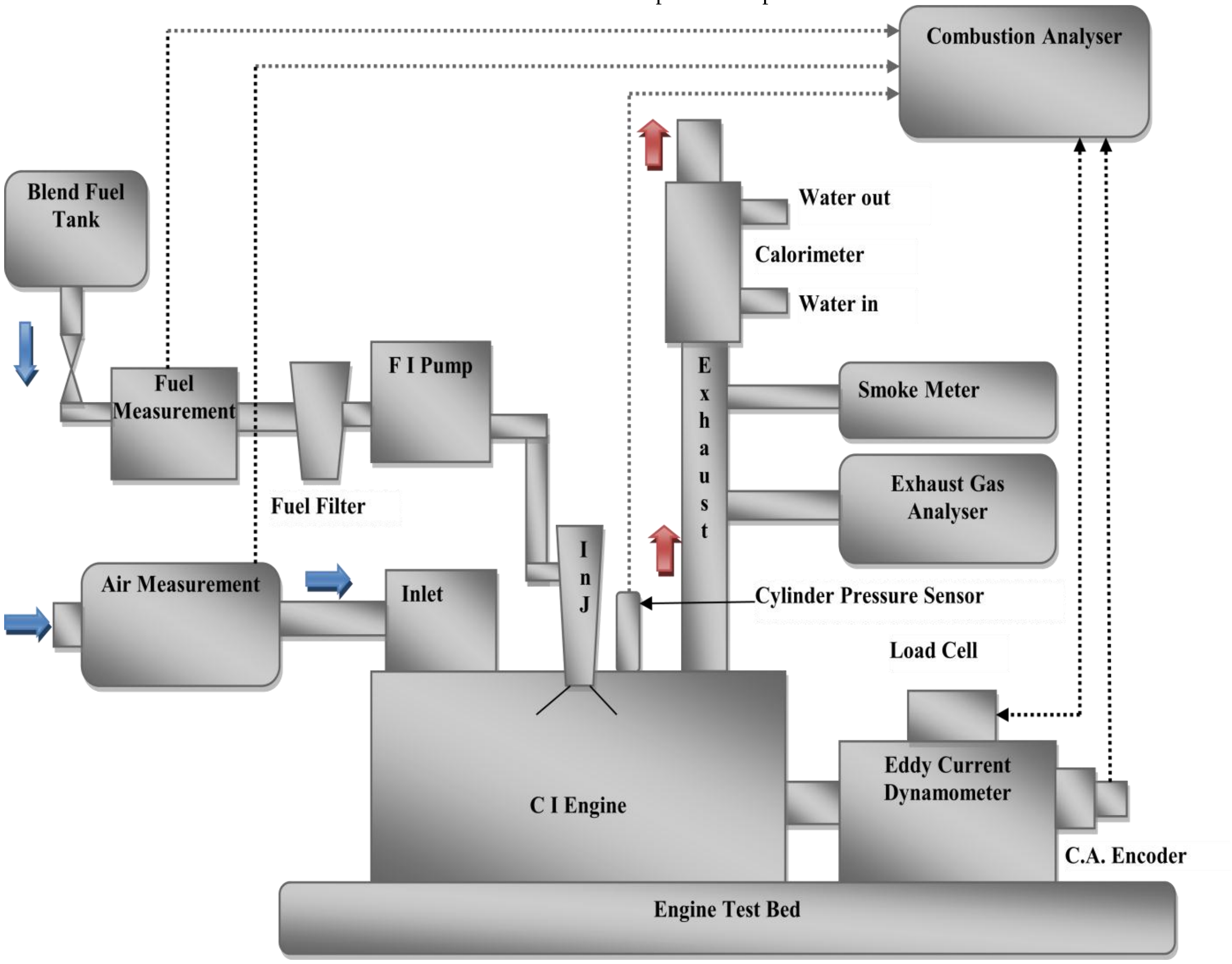

Figure 1. Schematic block diagram of engine test rig

TEST PROCEDURE

Initially, the engine is overhauled with necessary replacements and fresh lubricating oil is filled in the oil sump. Various measuring devices are calibrated as per norms. The engine tests are carried out at 25%, 50%, 75% and 100% of full load at 1500 rpm rated speed for all the test fuels. The rated speed of the engine is retained by adjusting fuel flow rate through a fuelling rack of the fuel injection pump. Engine temperature is kept constant throughout the tests by varying water flow rate. After every fuel test, the fuel tank and fuel injection system are cleaned. The engine is operated for sufficient time to consume any remaining fuel from the previous experiments. Once the engine warm up and reaches the stable operating conditions, the necessary engine combustion, performance and emission data is collected for every loading condition. This data is then recorded and analysed for various parameters.

RESULTS AND DISCUSSION

The experiments are carried out successfully up to 15% DEE addition with optimised ethanol-diesel blend fuel. Beyond this limit, the lubricity of the blends reduces and creates potential wear problems in sensitive fuel injector and fuel injection pump due to the reduction in kinematic viscosity and density of the blends than the acceptable limit [15].

Brake Thermal Efficiency

The addition of DEE to ethanol-diesel blends supplies higher cetane number and an amount of oxygen which has persuade on engine's combustion, performance and emissions. The brake thermal efficiency is the inverse of the product of the brake specific fuel consumption and the lower calorific value of the fuel. When operating on oxygenated fuels, the brake thermal efficiency is more delegate indication of the fuel economy [14]. The variation of engine brake thermal efficiency against BMEP for test fuels is shown in Figure 2. It is seen from figure that BTE has improved with DEE addition to ethanol-diesel blend fuel. The maximum BTE is achieved by DE8E10D blend for all loads as compared to other blends and neat diesel. However, at full load condition the BTE of DE5E10D and DE8E10D is observed maximum than other blends. The BTE of DE15E10D is increased by 15% than neat diesel at full load condition. The density, kinematic viscosity and bulk modulus of the oxygenated fuel play a noteworthy role on the enhancement of atomisation behaviour. Which improves the spray quality of low viscosity oxygenated blended fuels. Consequently, the fine droplets and a strong interface between fuel spray and surrounding gas perform well as compared to neat diesel. Also the combustion efficiency is enhanced because of heat losses in the cylinder are decreased due to lower flame temperature of DEE blend than that of neat diesel [15].

The other parameters like brake specific fuel consumption (BSFC) and brake specific energy consumption (BSEC) are almost the adverse of BTE and will not show any different physical meaning, hence they are not discussed here.

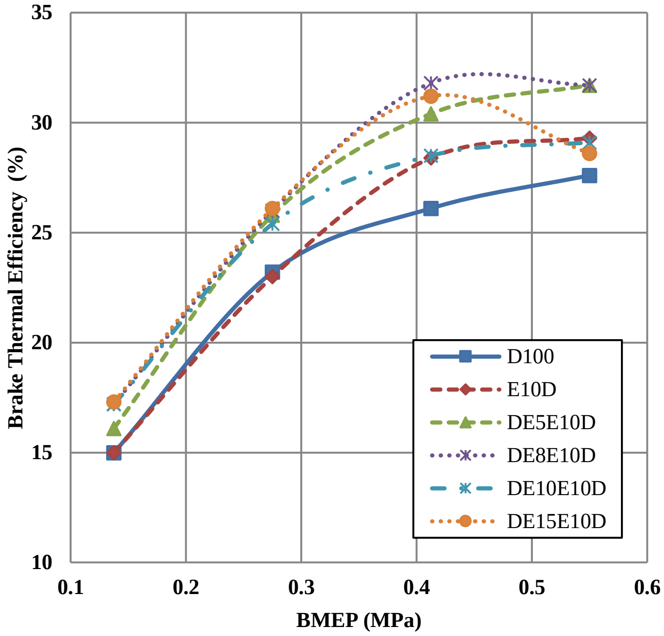

Figure 2. Variation of Brake Thermal Efficiency with respect to BMEP.

Smoke Emission

The heterogeneous combustion, poor mixing of the fuel with air and over-rich A/F ratio or partially evaporated fuel during cold start conditions leads to formation of smoke in diesel engine. Figure 3 illustrates the smoke opacity traces with respect to BMEP for test fuels. The general trend demonstrates the reduction in smoke opacity with addition of oxygenated DEE in the blends. The experimental results show that the 15% addition of DEE to the ethanol-diesel blend has the lowest smoke in overall and at full load condition. The smoke emission of DE15E10D is reduced by 6.25% than neat diesel at full load condition. This reduction in smoke emission is due to oxygen content in DEE which assists in an improved combustion than other blends and neat diesel fuel. Moreover, the smoke is produced mainly in the diffusive combustion phase; hence the addition of oxygenated DEE fuel leads to an improvement in diffusive combustion [16-17]. Rakopoulos et al. [15] reported that the reduction in smoke may be attributed to the engine running overall leaner due to fuel bound oxygen of DEE even in locally rich zones, which appears to have the dominating influence.

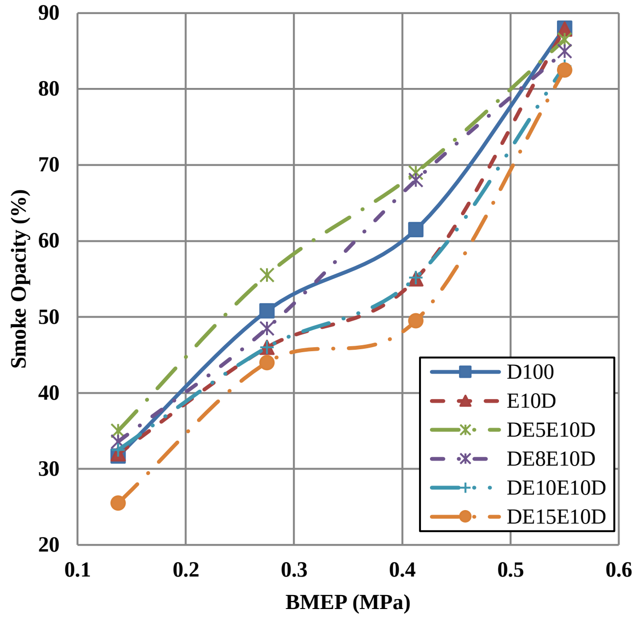

Figure 3. Variation of Smoke emission with respect to BMEP

NOx Emissions

The NOx called nitrogen oxides usually represents a mixture of NO and NO_2. In diesel engine the NO is usually the most abundant NOx and constitutes more than 70-90% of total NOx. The NOx emissions during the combustion process are determined by the factors like availability of oxygen, nitrogen content of the fuel itself, combustion temperature and the reaction time. The NOx produced is proportional to combustion efficiency. The better combustion efficiency increases the exhaust temperature, which consequently increases the NOx emission [13].

The variation of NOx emissions against BMEP is shown in Figure 4. It is observed that the NOx emissions are sharply reduced by addition of DEE to E10D blends than the neat diesel. This reduction is higher with higher DEE fraction in the blends. It can be seen that DE8E10D at full load condition and DE15E10D in overall shows the maximum reduction in NOx emissions. At full load condition the NOx emission of DE15E10D is reduced by 36% than neat diesel. This reduction in NOx can be attributed to three factors such as the combustion temperature lowering effect of DEE, engine running overall leaner due to oxygen concentration and the reduction in reaction time. Nevertheless, it is recognized that the fuel-bound oxygen is more effective than the external oxygen supplied by air in the production of NOx emissions [15].

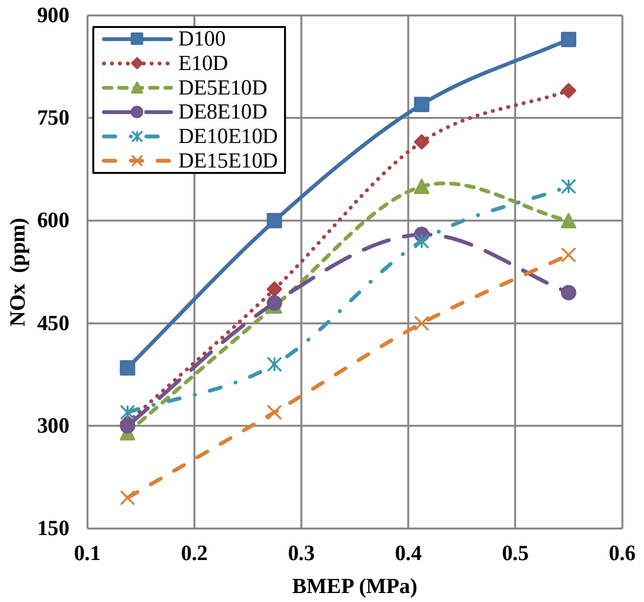

Figure 4. Variation of NOx emission with respect to BMEP

Carbon Monoxide Emission

Figure 5 illustrates the variation of Carbon Monoxide (CO) emission traces with respect to BMEP for DEE-ethanol-diesel blends at engine speed of 1500 rpm. The CO emissions of diesel engine mostly depend upon the physicochemical properties of the fuel. The overall test results indicates that with the addition of DEE to selected optimum ethanol-diesel blend, there is no significant difference at lower loads but at higher loads for larger amount of DEE addition a sharp increase in CO emission is observed. At full load condition the CO emission of DE15E10D is increased by 43% than neat diesel. The possible reason may be explained that the retarded injection timing retards the onset of combustion, which reduces the oxidisation process time, leaving more CO in the exhaust. Moreover, the theory of CO formation embraces that in the premixed combustion phase, the CO concentration increases rapidly to the maximum value in the flame zone. The CO produced via this path is then oxidised to CO_2 but at slower rate [14, 18].

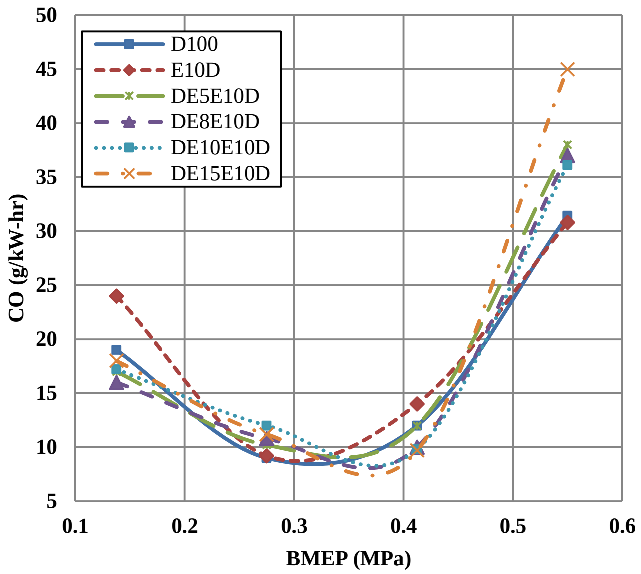

Figure 5. Variation of CO emission with respect to BMEP

Unburned Hydrocarbon Emission

Figure 6 illustrates the variation of total unburned hydrocarbon (HC) emission with respect to BMEP for DEE-ethanol-diesel blends at 1500 rpm engine speed. One can observe that the HC emissions of DEE-ethanol-diesel blends are higher than the neat diesel and ethanol-diesel blend and increased with increase in percentage of DEE in the blends. The HC emission of DE15E10D is increased by 42% than neat diesel at full load condition. Rakopoulos et al. [18] have reported that the increase in HC emission is primarily due to the higher heat of evaporation of the DEE causing slow evaporation, poor fuel-air mixing and the increase of the lean outer flame zone where flame is unable to exist.

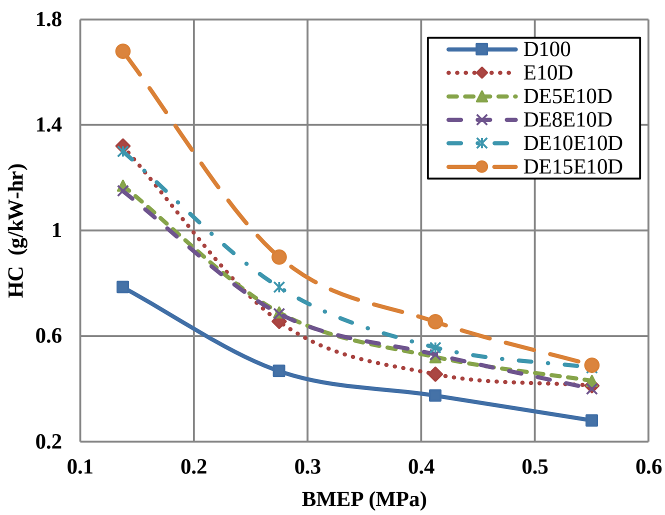

Figure 6. Variation of Unburned Hydrocarbon emission with respect to BMEP

CONCLUSIONS

Diethyl ether (DEE) seems to be one of the promising candidates as additive to ethanol-diesel blend fuel. The experimental results indicated that the addition of DEE up to 15% by volume with selected optimum 10% ethanol-diesel blend is possible. The lubricity reduction is one of the main reasons for keeping less than 15% DEE in the blends. The laboratory tests reveal that the DEE is completely miscible with diesel and ethanol fuel. The concentration of DEE in the DEE-ethanol-diesel blends increases the oxygen content, cetane number and reduces the density, kinematic viscosity and calorific value. The BTE has improved with DEE addition to ethanol-diesel blend and the maximum BTE is achieved by DE8E10D blend for all loads as compared to other blends and neat diesel.

The smoke emissions are reduced with increase in DEE percentage in the DEE-ethanol-diesel blends. The 15% addition of DEE to the ethanol-diesel blend has shown the reduction in smoke opacity by 6.25% and NOx emission by 36% at full load condition. The NOx emitted by DEE-ethanol-diesel blends are sharply reduced than the neat diesel and ethanol-diesel blend, with the reduction being higher with higher percentage of DEE fraction in the blends. However, it is recognized that the fuel-bound oxygen is more effective than the external oxygen supplied by air in the production of NOx emissions. The CO and HC emitted by all DEE-ethanol-diesel blends are found higher than the corresponding neat diesel.

The overall test result indicates that the trade-off between NOx and Smoke of diesel engine is reduced by adding oxygenated DEE to ethanol-diesel blends. The optimum blend ratio found is DE15E10D without any modifications in the engine.

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