

# Experimental Studies on the Combustion and Emission Characteristics of a Diesel Engine Fuelled with Used Cooking Oil Methyl Ester and its Diesel Blends

G Lakshmi Narayana Rao, S Sampath, K Rajagopal

**Abstract**—Transesterified vegetable oils (biodiesel) are promising alternative fuel for diesel engines. Used vegetable oils are disposed from restaurants in large quantities. But higher viscosity restricts their direct use in diesel engines. In this study, used cooking oil was dehydrated and then transesterified using an alkaline catalyst. The combustion, performance and emission characteristics of Used Cooking oil Methyl Ester (UCME) and its blends with diesel oil are analysed in a direct injection C.I. engine. The fuel properties and the combustion characteristics of UCME are found to be similar to those of diesel. A minor decrease in thermal efficiency with significant improvement in reduction of particulates, carbon monoxide and unburnt hydrocarbons is observed compared to diesel. The use of transesterified used cooking oil and its blends as fuel for diesel engines will reduce dependence on fossil fuels and also decrease considerably the environmental pollution.

**Keywords**—Combustion characteristics, Diesel engine, Emission characteristics, Used cooking oil

## I. INTRODUCTION

THE large increase in number of automobiles in recent years has resulted in great demand for petroleum products. With crude oil reserves estimated to last for few decades, there has been an active search for alternate fuels. The depletion of crude oil would cause a major impact on the transportation sector. Of the various alternate fuels under consideration, biodiesel, derived from vegetable oils, is the most promising alternative fuel to diesel due to the following reasons [1]-[3].

1. Biodiesel can be used in the existing engine without any modifications.
2. Biodiesel is made entirely from vegetable sources; it does not contain any sulfur, aromatic hydrocarbons, metals or crude oil residues.

3. Biodiesel is an oxygenated fuel; emissions of carbon monoxide and soot tend to reduce.
4. Unlike fossil fuels, the use of Biodiesel does not contribute to global warming as CO<sub>2</sub> emitted is once again absorbed by the plants grown for vegetable oil /biodiesel production. Thus CO<sub>2</sub> balance is maintained.
5. The Occupational Safety and Health Administration classifies biodiesel as a non-flammable liquid.
6. The use of biodiesel can extend the life of diesel engines because it is more lubricating than petroleum diesel fuel.
7. Biodiesel is produced from renewable vegetable oils/animal fats and hence improves the fuel or energy security and economy independence.

A lot of research work has been carried out to use vegetable oil both in its neat form and modified form. Studies have shown that the usage of vegetable oils in neat form is possible but not preferable [4]. The high viscosity of vegetable oils and the low volatility affects the atomization and spray pattern of fuel, leading to incomplete combustion and severe carbon deposits, injector choking and piston ring sticking. The methods used to reduce the viscosity are

- \* Blending with diesel
- \* Emulsification
- \* Pyrolysis
- \* Transesterification

Among these, the transesterification is the commonly used commercial process to produce clean and environmental friendly fuel [5]. Methyl / ethyl esters of sunflower oil [6],[7], rice bran oil [8], palm oil [9], mahua oil [10], jatropha oil [11], karanja oil [12], soybean oil [13], rapeseed oil [14] and rubber seed oil [15],[16] have been successfully tested on C.I. engines and their performance has been studied. The sunflower oil, soybean oil and palm oil are edible oils and also, are expensive. Hence they are not suitable for use as feedstock for biodiesel production in economical way. The non-edible oils such as jatropha oil and karanja oil, even though attractive due to their low cost, requires considerable amount of land and time for cultivation. These uncertainties can prevent large-scale production and marketing of biodiesel.

Used cooking oils provide a viable alternative to diesel, as they are easily available. These contain some

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degradation products of vegetable oils and foreign material. These impurities can be removed by heating and filtration. Hence this does not prevent its usage as feedstock for biodiesel production [17]. It has been reported that the cetane number of used cooking oil methyl ester is around 49 and it demonstrates its potential to replace diesel [18]. However not much work has been carried out on combustion and emission studies of used cooking oils as diesel engine fuels. Earlier experimental work on used cooking oil supports some favorable results on engine performance and emission characteristics [19], [20]. Canakci [21] studied the potential of restaurant waste oils as biodiesel feed stock by analyzing their free fatty acid and moisture content. Pugazhvadivu et al. [22] had carried out engine tests using preheated waste cooking oil. Cetinkaya et al. [23] had conducted road test using Renault Megane make automobile fueled with methyl esters of waste cooking oil. Breuer [24] studied the effect of fuel properties on heat release through experiments conducted with Rapeseed Oil and its Methyl Ester. Vaughn et al. [25] arrived at the ignition delay of a number of Bio-Esters by droplet ignition delay experiments. Kinoshita et al. [26] evaluated the combustion characteristics of biodiesels derived from coconut oil and palm oil, while Sinha et al. [27] investigated the incylinder pressure and heat release patterns of 20% rice bran oil methyl ester- diesel blend. Hamasaki et al. [28] had analyzed the rate of heat release of waste vegetable oil methyl ester.

In this work, the combustion behavior of UCME is reported. The explanation of the observed performance and emissions has been based on inferences drawn from combustion characteristics. Moreover this paper presents a comprehensive analysis of UCME and its blends with diesel.

## II. MATERIALS AND METHODS

### A. Preparation of Used Cooking Oil Methyl Ester (UCME)

Used sunflower oil collected from the restaurants is considered as feedstock for the biodiesel production. Transesterification is a chemical process of transforming large, branched, triglyceride molecules of vegetable oils and fats into smaller, straight chain molecules, almost similar in size to the molecules of the species present in diesel fuel. The process takes place by reacting the vegetable oil with an alcohol in the presence of catalyst. Methyl esters are preferred as methanol is non hygroscopic and is less expensive than other alcohols. In general, due to high value of free fatty acids (FFA) of used cooking oils, acid catalysed transesterification is adopted [29],[30]. However, FFA of the feedstock used in this work is less and hence alkali catalyzed transesterification process [31]-[33] is employed for the conversion of used cooking oil into ester.

The used cooking oil is preheated in a reactor to remove the moisture. Potassium methoxide is prepared by dissolving potassium hydroxide in methanol. Various concentration of KOH in the methoxide was prepared and the process is optimized for the maximum yield. For the optimized KOH

concentration, alcohol proportion also optimized to obtain the maximum yield. Methoxide is mixed with preheated oil and the reaction carried out under nominal speed stirring by a mechanized stirrer and at a constant reaction temperature of 55°C for 2 hours. After 3 hours of settling period, ester separates as an upper layer and glycerol settles at bottom separated by decantation. These esters is washed with warm water to remove impurities and separated. Experimentally the process parameters are optimized. The optimum proportions are for one litre of used cooking oil, the requirement of methanol and KOH are 200 ml and 7.75g respectively. With this proportion from one litre of used cooking oil, 920 ml of UCME was produced. The important properties of used cooking oil, UCME and diesel are given in Table 1. The fatty acid profile of UCME is Palmitic – 7.4%, Stearic – 3.4%, Oleic – 41.4%, Linoleic – 46.6% and others – 1.2%. XX%UCME denotes the % volume of UCME in UCME – diesel blends. For example, 20%UCME refers to 20% of UCME and 80% of diesel in the blend.

TABLE I  
PROPERTIES OF DIESEL AND UCME

Property	Unit	Used Cooking Oil	UCME	Diesel
Density	kg/m <sup>3</sup>	920	885	821
Kinematic viscosity	cSt	4.291	4.73	3.52
Flash point	°C	290	142	49
Calorific value	kJ/kg	36,750	38,650	44,300
Acid value	mg KOH/g	3.05	0.08	0.20

### B. Engine Tests

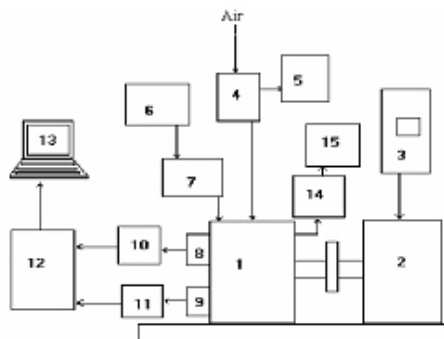
A single cylinder, 4.4 kW direct-injection air-cooled stationary C.I. engine coupled with swinging field electrical dynamometer is used for the experimental study and the detailed technical specifications are given in Table II. Fig.1 shows the schematic diagram of the experimental set-up.

TABLE II  
ENGINE SPECIFICATIONS

Engine Type	Four stroke, constant speed, direct injection, diesel engine
Make and Model	Kirloskar and TAF1
Maximum Power	4.4 kW @ 1500 RPM
Maximum Torque	28 N-m @ 1500 RPM
Bore	87.5 mm
Stroke	110 mm
Compression Ratio	17.5:1
Injection Timing	23.4° bTDC

The engine is interfaced with avl indimeter software for the measurement of combustion parameters. the pressure values

are averaged over 100 cycles.  $\text{no}_x$ ,  $\text{hc}$  and  $\text{co}$  emissions are measured using a 5 gas analyzer and the concentrations of particulate matter are measured using avl 415 variable sampling smoke meter. the engine tests are carried out at various loads with diesel, ucme and its blends.



1. Diesel Engine, 2. Electrical Dynamometer, 3. Dynamometer controls, 4. Air box, 5. U-tube manometer, 6. Fuel tank, 7. Fuel measurement, 9. TDC position sensor, 10. Charge amplifier, 11. TDC amplifier circuit, 12. A/D card, 13. personal computer

Fig. 1 Experimental set up

### III. RESULTS AND ANALYSIS

This paper compares ignition delay, rate of pressure rise, peak pressure, in-cylinder pressure variation, heat release rate, specific fuel consumption, brake thermal efficiency and exhaust emissions of UCME and its blends with those of diesel.

#### A. Combustion Characteristics

This section describes the effects of percentage of UCME in the blend on combustion characteristics i.e. ignition delay, rate of pressure rise, peak pressure, heat release rate based on experimental results.

##### 1. Ignition Delay

Ignition delay of fuel is a significant parameter in determining the knocking characteristics of C.I. engines. The cetane number of a fuel, which indicates the self-igniting capability, has a direct impact on ignition delay. The higher the cetane number, the shorter the ignition delay, and vice versa. Fig.2 shows the ignition delay of diesel, UCME and its blends. It is observed that the ignition delay periods of UCME and its blends are significantly lower than that of diesel and are decreasing with increase in % UCME in the blend. This is due to the fact that Oleic and Linoleic fatty acid methyl esters present in the UCME split into smaller compounds when it enters the combustion chamber resulting in higher spray angles and hence causes earlier ignition [19]. This indicates that UCME and its blends have higher cetane number compared to diesel. It is noticed that for all test fuels the reduction in ignition delay increases with the increase in load. This may be due to higher combustion chamber wall temperature and reduced exhaust gas dilution at higher loads.

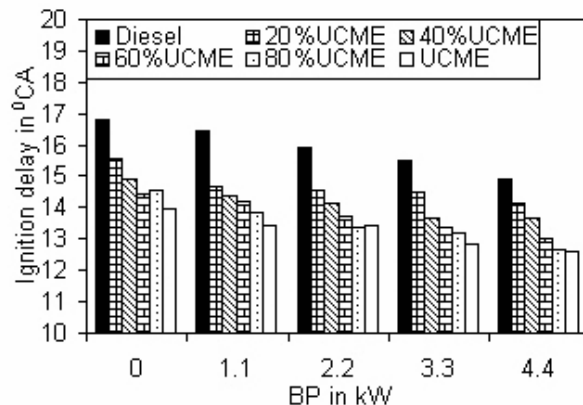


Fig. 2 Comparison of ignition delay

##### 2. Peak Pressure

The variation of peak pressures with respect to brake power for diesel, UCME and its blends is shown Fig.3 It can be seen that the peak pressure is slightly higher for UCME and its blends when compared to that of diesel. This is due to the lower ignition delay of UCME and its blends. The oxygen content of UCME, which results in better combustion, may also result in higher peak pressure compared to diesel.

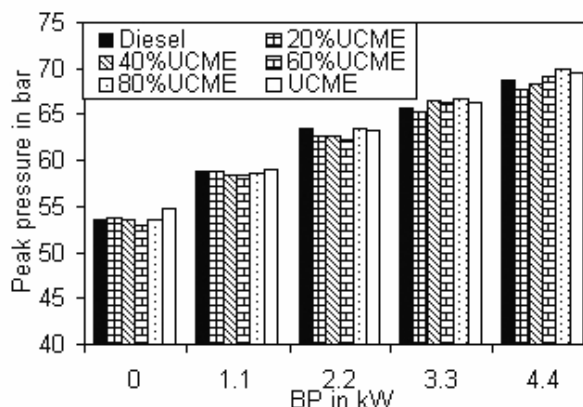


Fig. 3 Comparison of peak pressure

##### 3. Rate of Pressure Rise

Fig.4 shows the rate of pressure rise with crank angle at rated load for the test fuels. Similar trend was noticed at all other loads. All the tests are performed at an injection timing  $23.4^\circ$  bTDC. The analysis is concerned with the evaluation of rate of pressure rise for crank angles between  $9^\circ$  bTDC and  $4^\circ$  aTDC, since the maximum Rate of Pressure Rise occurs within this period for all fuel blends. It can be observed that the rate of pressure rise for diesel is higher compared to those of UCME and its blends. This is due to the longer ignition delay and shorter combustion duration of diesel compared to UCME and its blends.

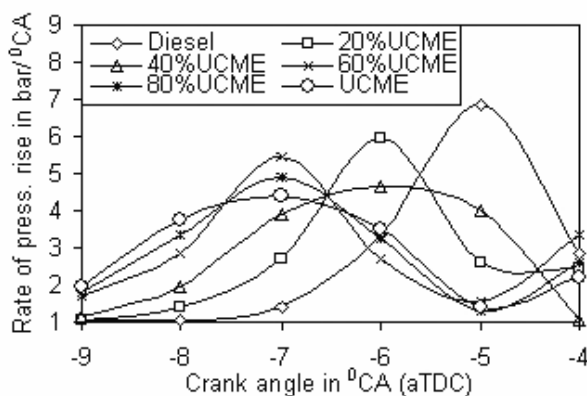


Fig. 4 Comparison of Rate of Pressure Rise

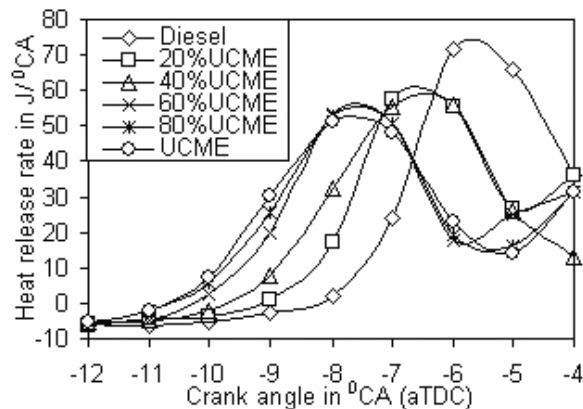


Fig. 6 Comparison of rate of heat release

#### 4. Pressure Variation with Crank Angle

The pressure variation in the cycle is important in the analysis of the performance characteristics of any fuel. The pressure variations of UCME-diesel blends at rated load are shown in Fig.5. UCME and its blends follow the similar pattern of pressure rise to that of diesel at all load conditions. Table 5 indicates that, when compared to diesel oil, the values of pressure data of 20%UCME and 40%UCME are lower while for 60%UCME, 80%UCME and UCME are higher. These distinct differences may be due to variations of viscosity and heating value with percentage of UCME in the fuel.

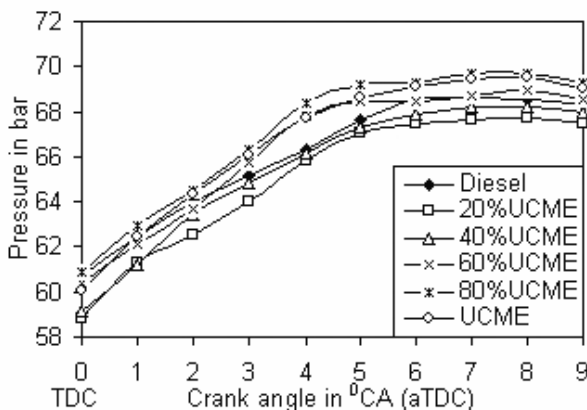


Fig. 5 Comparison of In-cylinder pressure

#### 5. Rate of Heat Release

A thorough knowledge of the heat release pattern of a fuel is essential for the analysis of  $\text{NO}_x$  formation inside the combustion chamber and the cooling system requirements of the engine. The comparison of heat release rate variations for UCME and its blends with diesel is shown in Fig.6. It is observed that the maximum heat release rate of 71.459 J/Deg. CA is recorded for diesel at 6° bTDC, while UCME records its maximum heat release rate of 51.481 J/Deg.CA at 8° bTDC. As the percentage of UCME in the blend increases, the maximum heat release rate decreases and the crank angle at which it takes place advances.

#### B. Performance Characteristics

Engine performance characteristics are the major criterion that governs the suitability of a fuel. This study is concerned with the evaluation of brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) of the UCME-diesel blends.

##### 1. Brake Specific Fuel Consumption (BSFC)

UCME has lower calorific value than that of diesel. Hence the specific fuel consumption is slightly higher than that of diesel for UCME and its blends. Fig.7 shows the BSFC of various blends of UCME-diesel.

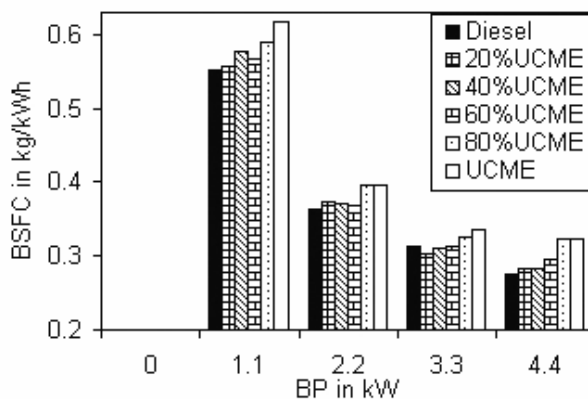


Fig. 7 Comparison of brake Specific fuel consumption

##### 2. Brake Thermal Efficiency (BTE)

Fig.8 shows that brake thermal efficiency of UCME and its blends is lower compared to that of diesel. At rated load the BTE of UCME is lower than that of diesel by 2.5%. The BTE of blends of UCME lie between those of diesel and UCME at all loads. Since the engine is operated under constant injection advance and UCME has a smaller ignition delay, combustion is initiated much before TDC is reached. This increases compression work and more heat loss and thus reduces the brake thermal efficiency of the engine. This can also be explained by the fact that maximum efficiency is obtained when most of the heat is released close to TDC [34]. The start of heat release much before TDC for UCME and its

blends results in larger deviation from the ideal cycle and hence lower thermal efficiency is recorded. Also it is noticed from the Fig.8, that the decrease in BTE is not proportional to the increase in % UCME in the fuel. This variation is due to better lubricating properties of UCME as compared to diesel.

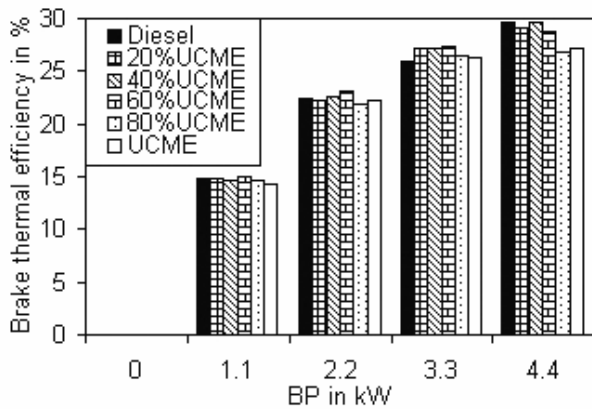


Fig. 8 Comparison of brake thermal efficiency

### C. Emission Characteristics

With problems like global warming, ozone layer depletion and photochemical smog in addition to widespread air pollution, automotive emissions are placed under the microscope and every possible method is attempted to reduce emissions. Hence this study compares the emissions of pollutants- nitrogen oxides, carbon monoxide, unburned hydrocarbon emissions and smoke of UCME and its blends with diesel.

#### 1. Exhaust gas temperature

Fig.9 shows the exhaust gas temperature variations for test fuels with load. It is observed that the exhaust gas temperature increases with load because more fuel is burnt at higher loads to meet the power requirement. It is also observed that the exhaust gas temperature increases with percentage of UCME in the test fuel for all the loads. This may be due to the oxygen content of the UCME, which improves combustion and thus may increase the exhaust gas temperature

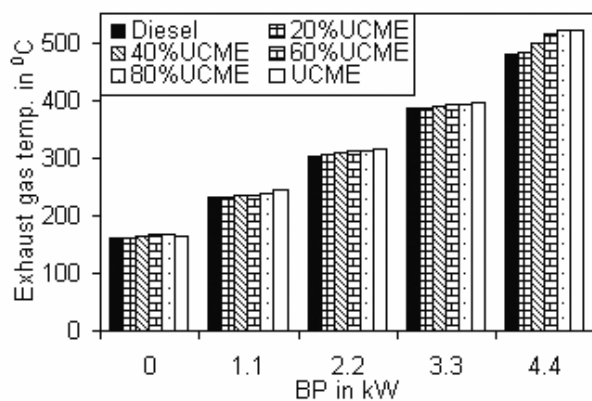


Fig. 9 Comparison of exhaust gas temperature

#### 2. Nitrogen Oxides Emission

Fig.10 shows gradual increase in the emission of nitrogen oxides ( $\text{NO}_x$ ) with increase in percentage of UCME in the fuel. The  $\text{NO}_x$  increase for UCME may be associated with the oxygen content of the UCME, since the oxygen present in the fuel may provide additional oxygen for  $\text{NO}_x$  formation. Another factor causing the increase in  $\text{NO}_x$  could be the possibility of higher combustion temperatures arising from improved combustion. It has to be noted that a larger part of the combustion is completed before TDC for UCME and its blends compared to diesel due to their lower ignition delay. So it is highly possible that higher peak cycle temperatures are reached for UCME and its blends compared to diesel. However  $\text{NO}_x$  can be controlled by adopting Exhaust Gas Recirculation and by employing suitable catalytic converters.

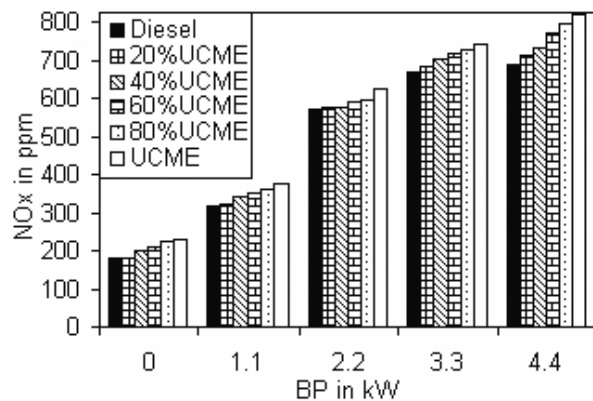


Fig. 10 Comparison of Nitrogen Oxides

#### 3. Carbon Monoxide Emission

Fig.11 shows that carbon monoxide emissions are greatly reduced with the addition of UCME to diesel. The emission of CO is reduced by 15% for 20%UCME and by 50% for UCME when compared to diesel at rated load condition. CO is predominantly formed due to the lack of oxygen. Since UCME is an oxygenated fuel, it leads to better combustion of fuel resulting in the decrease in CO emission. Reduction in CO emissions is a strong advantage in favor of UCME.

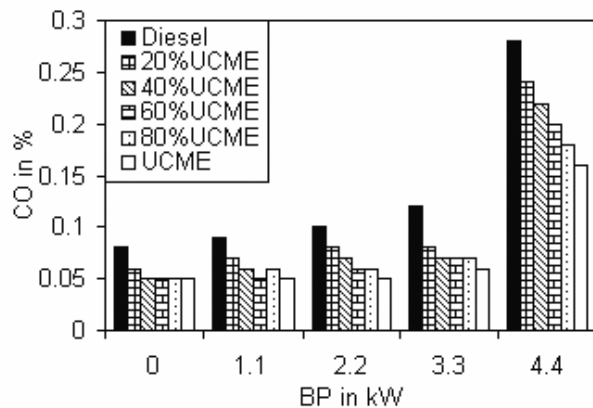


Fig. 11 Comparison of carbon monoxide

#### 4. Unburnt Hydrocarbons Emission (UBHC)

The unburnt hydrocarbons (UBHC) emissions with UCME and its blends are compared with diesel in Fig.12. UBHC emissions are reduced over the entire range of loads for UCME – diesel blends. It decreases with increase in % of UCME in the blend. Since the UCME is an oxygenated fuel, it promotes combustion and results in reduction in UBHC emissions.

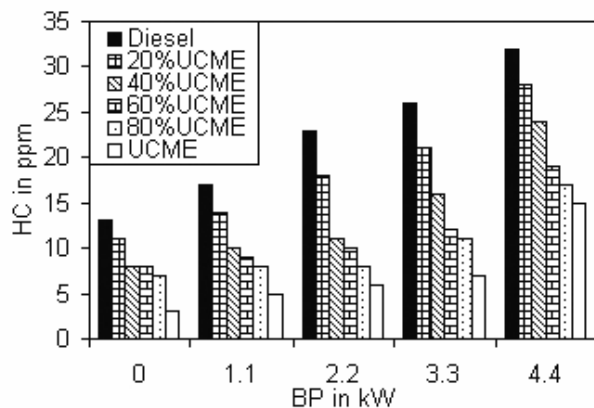


Fig. 12 Comparison of hydrocarbon emissions

#### 5. Smoke Intensity

Smoke or soot primarily comprises of carbon particles. The improved combustion characteristics of UCME may lead to fewer unburnt fuel particles impinging on cylinder walls (wall quenching). Table 3 presents the smoke intensity of Diesel, UCME and its blends. A vast reduction in smoke intensity is observed with increase in percentage of UCME in the blend, especially at high loads. UCME and its blends as fuel in diesel engines significantly reduce smoke.

TABLE III  
COMPARISON OF SMOKE INTENSITY

Brake Power (kW)	Smoke intensity in mg/m <sup>3</sup>					
	Diesel	20% UCME	40% UCME	60% UCME	80% UCME	100% UCME
0	2	2	3	2	2	2
1.1	9	6	5	5	5	7
2.2	19	16	13	7	10	15
3.3	82	37	30	24	20	29
4.4	206	115	87	90	78	72

#### IV. CONCLUSION

The performance, emissions and combustion characteristics of a 4.4 kW DI compression ignition engine fuelled with UCME and its blends have been analysed, and compared to the baseline diesel fuel. The results of present work are summarized as follows:

The ignition delay of UCME and its blends is found to be lesser as compared to that of diesel. The peak pressure of UCME-diesel is higher than that of diesel.

The engine develops maximum rate of pressure rise and maximum heat release rate for diesel compared to UCME and its blends. With increase in percentage of UCME in the blend, the maximum rate of pressure rise and maximum heat release rate decrease.

The specific fuel consumption increases with increase in percentage of UCME in the blend due to the lower calorific value of UCME. The brake thermal efficiency decreases with increase in percentage of UCME in the fuel.

Increase in oxygen content in the UCME-diesel blends as compared to diesel results in better combustion and increase in the combustion chamber temperature. This leads to increase in NO<sub>x</sub>. UCME recorded higher values of NO<sub>x</sub> compared to diesel at rated load.

Emissions of CO and UBHC decrease with increase in percentage of UCME in the blend. It is also observed that there is a significant reduction in smoke intensity especially at higher loads even with 20% UCME

The used cooking oil as feedstock for transesterification reduces the production cost of biodiesel. UCME satisfies the important fuel properties as per ASTM specification of biodiesel and improves the performance and emission characteristics of engine significantly.

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