

Study of Biodiesel Emissions and Carbon Mitigation in Gas Turbine Combustor

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ABSTRACT: The energy security and reduction of carbon emissions have accelerated the R&D of the alternative fuels in the transport, heating and power generation sectors in last decade. The heating and power generation sectors are two of the major contributors to carbon dioxide emissions, which are due to the combustion of petroleum fuels. A gas turbine combustor test rig was used to study the combustion and emission characteristics of waste cooking oil methyl ester (WME) biodiesel. A 140mm diameter atmospheric pressure premixed combustion test rig was used at 600K inlet air temperature and Mach number 0.017. The tests were conducted using pure WME and blend with kerosene. The central fuel injection was used for liquid fuels and wall injection was used for NG (Natural Gas). The exhaust samples for smoke and gaseous emissions (NOx, UHC, CO and CO₂) have been analysed on dry basis and corrected to 15% O₂ over range of different fuel rate. The results showed that the biodiesel had lower CO, UHC emissions and higher NOx emissions than the kerosene. The blend B20 had lowest NOx emissions comparing with pure biodiesel (B100) and B50. The optimum conditions for WME with lowest emissions were identified. The carbon dioxide emissions per 100 megawatts of heat generated for each fuel were calculated. The relative carbon emissions and mitigations by biodiesel were compared. The results can be used to estimate pollutant emissions and carbon reductions by biodiesel in power generation industry and other sectors where gas turbine engines are used.

KEYWORDS: Biodiesel, Gas turbine, Gaseous Emissions, carbon mitigation.

I. INTRODUCTION

During the last decade, global warming from the increase in greenhouse gases has become a major scientific and political issue. The level of these gases is increasing in the atmosphere as a result of human activity such as fossil fuel combustion (oil, coal and natural gas) and land use (largely deforestation)[1]. Fossil fuel is a primary source for the energy supply and Figure.1 shows that the petroleum and natural gas comprised of ~60% of energy supply worldwide in 2005[2].

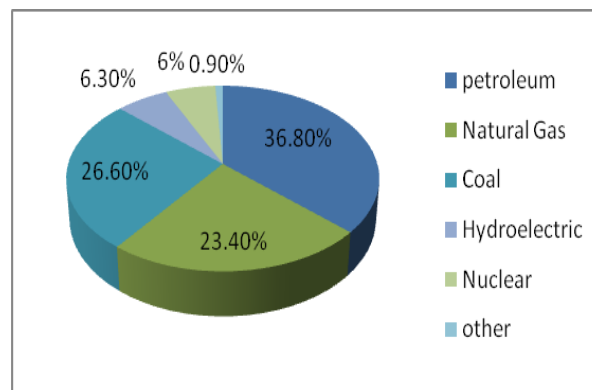


Fig.1 : Fractions of sources for Energy production in 2005[2].

The main greenhouse gases (GHGs) that are produced by human activities and have direct contributions to global warming potentials are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and some special chemicals (halogenated compounds) and their proportional contributions are shown in Figure.2. [3]. CO₂ is a dominant GHG and its level in the atmosphere has been increased by some 25% during the past 200 years and continuing to increase at 0.4% per year[4].The results showed that the average earth surface temperature will increase by some 2° to 6°C and sea level will rise of between 50 and 200 centimetres in this century[5, 6]. Figure.3 shows the three major contributors of carbon dioxide emissions by sectors: power plants, factories and home heating systems and transport[3]. Each sector contributes one third of carbon dioxide emissions.

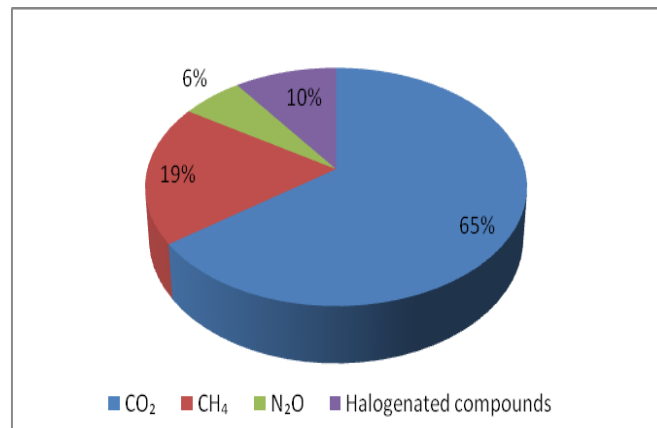


Fig.2: Proportional contributions of greenhouse gases to climate change[1]

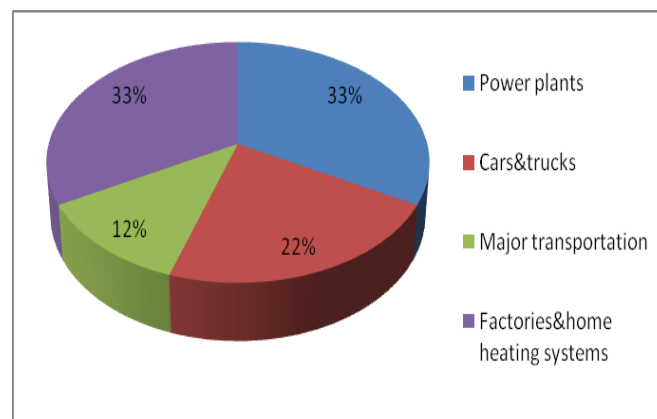


Fig.3: Contributions of each sector to CO₂ emissions[3]

The concerns of environmental impacts and energy security have led the R&D of alternative energy sources such as biofuels, solar and wind energy. Biofuels have attracted huge attention in different countries due to their renewability and environmental benefits. Biofuels include bio-alcohols, biodiesel, biomass and other biomass derived fuels. Biodiesel is one of the most popular biofuels being used in the transport sector. Many studies have shown that the characteristics of biodiesel is very close to diesel fuel and can be used in diesel engine with little or no modification[7]. Moreover, the combustion of biodiesels shown a reduction in smoke opacity, particulate matter (PM), hydrocarbons and carbon monoxide emissions in the exhaust gas compared with diesel fuel[8]. Thus, the results showed significant reduction of smoke and gases emissions with biodiesel blends and the optimum ratios for biodiesel/diesel were 20/80 and 30/70[8]. One of the main drawbacks of biodiesel is the cost and sustainability. The use of waste cooking oils is one way to reduce the cost of biodiesel and utilise the waste [8].There are substantial researches on the applications of biodiesel on diesel engines but the studies on the applications of biodiesel on gas turbine engines are limited. This paper will assess and compare the environmental impact of waste cooking oil methyl ester (WME) and kerosene using a radial swirler industrial low NO_x gas turbine combustor under atmospheric pressure and 600K preheated air.

A. Biodiesel sources : In the last century petroleum fuel have been playing an important role in transportation, industrial growth with agricultural and energy sector [9, 10]. Depletion of fossil fuels and increasing concerns of environmental impacts have led scientists to identify alternative fuel sources [10, 11]. Biofuels such as biodiesel have attracted more and more attentions recently and become alternative fuels to liquid fossil fuels due to its renewability and its environmental benefits [9, 11, 12]. Biodiesel is one of the best available sources and promising alternative fuels to liquid fossil fuel [9, 10]. Biodiesel can be made from alcohol and vegetable oils or animal fats which are both agriculturally derived products[8]. Biodiesel is biodegradable and nontoxic and defined as the monoalkyl esters of long chain fatty acids derived from renewable feed stocks like vegetable oils or animal fats[13, 14]. Although there are over 350species of oil producing plants, only a few can potentially be used for biodiesel productions such as rapeseed, sunflower, soybean and oil palm[10]. Figure.4 gives the fractions of commonly used oil crops worldwide in terms of annual oil yield[15]

Rapeseed oil represents the largest contribution of world biodiesel production with 84%, whereas palm and soybean are the lowest[15]. However, the rapeseed oil is not the one having highest oil yield and instead the oil palm gives the highest harvest and oil yield per unit of land. The molecule of vegetable oil is composed of three fatty acid chains attached to a molecule of glycerine and known as triglycerides[16]. Many researchers have concluded that vegetable oils have a great potential to be alternative fuels for diesel engines[15]. However, using raw vegetable oils for diesel engines can cause numerous engine problems. The high viscosity and low volatility of oils compared with diesel lead to engine cold start problems, engine deposits, injector coking and piston ring sticking[7]. These problems can be solved by two ways: heating the vegetable oils to reduce the viscosity and lower the emissions or through transesterification of vegetable oils to form an ester (biodiesel) to reduce the viscosity [10, 17].

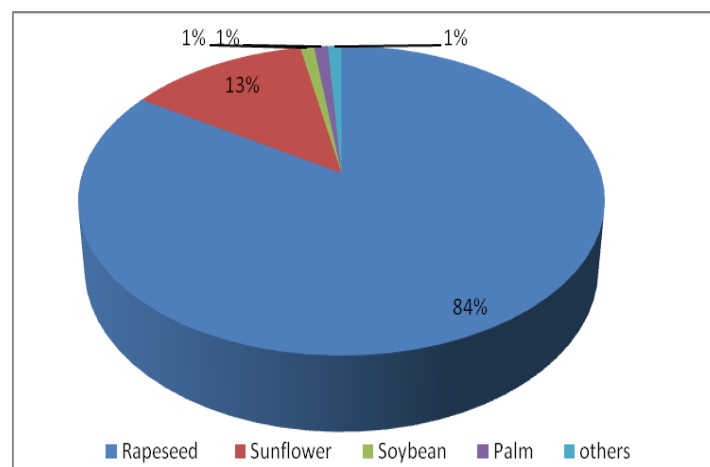


Fig. 4: Oil crops yield for biodiesel[15].

B. Biodiesel production process : Transesterification is defined as chemical reaction of vegetable oils or animal fats with alcohol in the presence of catalyst to form fatty acid methyl esters (FAME) and include glycerol by-product.[17-19]. Methanol, ethanol, propanol, butanol and amyl alcohol are alcohols used in transesterification process. Methanol is a most commonly used alcohol in this process due to its cost and its physical and chemical properties that can make the reaction with triglycerides quicker[14]. It was found that a 3:1 molar ratio of alcohol to triglycerides is needed to complete the transesterification process. Nevertheless, to improve the reaction rate, catalyst (alkalis, acids) or enzymes are usually used[14, 19].Moreover, alkali catalyst has been most often used commercially due to their fast reaction rate than its acid catalyst counterpart [20]. The typical alkali catalysts used in transesterification process are sodium hydroxide, potassium hydroxide or alkali methoxides[11]. However, acid –catalyzed transesterification has less usage because it has relatively slow reaction rate and its insensitivity to free fatty acids in feedstock oil than its alkali catalyst counterpart[19]. Sulphuric acid, sulfonic acids and hydrochloric acid are used as acid catalysts; sulphuric acid is the most commonly used in the reaction as acid catalyst[14, 19]. Nevertheless, acid –catalyzed transesterification can be used if there is more water and free fatty acid (more than 1) in the triglycerides [14].

C. Characteristics of biodiesel : Biodiesel is sulphur-free, non-toxic, biodegradable, oxygenated compounds and renewable fuels and has high cetane numbers. The major advantage of biodiesel is the reduction of CO₂ emissions. Many researchers have shown that the properties of biodiesel are similar to diesel fuel. Therefore, biodiesel can be used in diesel engine with little or no modification of the engines[16]. It shows that the density,

cetane number, pour point and flash point of biodiesel are higher whereas the heating value is about 10% lower compared to diesel. The kinematic viscosity of both fuels is similar. Moreover, biodiesel prolongs the engine life and has better lubricating qualities than fossil fuels. However, there are some drawbacks of biodiesel such as reduced energy density which increases mass fuel consumption and the higher cost of production than diesel [16]. The use of waste cooking oils and animal fats for biodiesel production provides not only a resource for biodiesel but also saving the environment as it avoids these oils and fats pouring into sewer systems which is harmful for the environment and human health [17, 18].

II. MATERIAL AND METHODS

A. Rig Description : Premixed Gas turbine combustor test rig was used to study the combustion and emission characteristics of biodiesel fuel. The apparatus used for the combustion experiments consisted of a combustion chamber, an air supply line, venturi air flow meter, 250mm diameter air plenum chamber, a fuel supply line and an exhaust gas analyse system. The combustion experiments were carried out at atmospheric pressure. To ensure high gas temperature of compressed air in the system air was heated to the required inlet temperature (600K) by a 150KW electrical heater. The primary zone combustion chamber was 6.4mm thick stainless steel, cylindrical shape with an inner diameter of 140mm and length of 330mm. Thus, a premixing fuel injector with holes on centres of equal area, 2m long and 76mm diameter mixing tube was used to inject biodiesel and kerosene in this study. The flame stabilizer was positioned in between the flame tube and the mixing tube.

The combustor was positioned in parallel in the test room and supplied by air from two independent approach pipes which connected to the air supply pipe downstream of the electrical heaters. The inlet temperature (of 600K) was measured 100mm upstream of the Swirler using chrome-alumel type K thermocouple and investigated at $M=0.017$. This Mach number typically represents ~40% of the total combustor airflow entering the lean primary zone through the radial swirler. The ignition was carried out by electrical discharge from the spark igniters.

B. Emission Measurement : Mean exhaust gas samples were obtained using an 'X' configuration stainless steel water cooled probe with 40 holes at centres of equal area. The sample gases were passed into a 190°C heated sample line and on through a 190°C heated filter and pump to a 190°C heated gas analysis system. The gas analyses results were processed to provide air fuel ratio, combustion efficiency and mean adiabatic flame temperature. The NO_x emissions were measured hot on wet gas basis using a chemiluminescence NO_x analyser (signal Instruments, UK) with vacuum ozone reaction chamber. It had a minimum scale of 1-4ppm with a 0.05ppm resolution. Whereas, the unburnt hydrocarbons was measured using a heated FID. However, the CO and CO₂ were measured on a dry gas basis using NDIR with luft cell detectors (ADC). The gas analysis results were processed to provide an air to fuel ratio and mean adiabatic flame temperature and all emissions will be corrected to 15% O₂ over a range of different fuel rate.

C. Fuel preparation and injection : Kerosene was stored in a 200 litre barrel whereas WME and blends were stored in a 40 litre tank. They were pumped from the barrel or tank and delivered to injection fuel points after passing through rotameters for measuring fuel flow. Two rotameters were used with different measurement ranges. These two rotameters were calibrated for kerosene, WME and blends respectively as the density for these liquid fuels are different and thus the mass flow is different for the same indicated readings

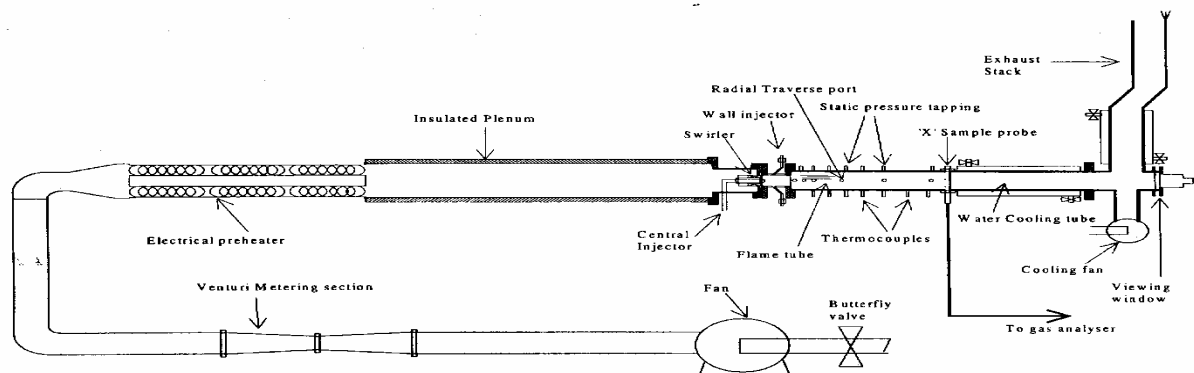


Fig.5: combustion Rig

Liquid fuels (B100, B50, B20 and Kerosene) were injected and premixed with incoming air in a premixed fuel injector with holes on centres of equal area. The air fuel ratio (equivalence ratio) is increased in small steps by increasing fuel flow rate whereas keeping air flow rate constant. The gas sample for smoke and gaseous emissions (NO_x, NO, UHC, CO and CO₂) have been analysed on dry basis and corrected to 15% O₂ over the range of different fuel rate.

III. RESULTS AND DISCUSSIONS

A. UHC, CO & NO_x Emissions : All emissions results are corrected to 15% oxygen and plotted as a function of the equivalence ratio for 600K inlet temperature and Mach number of 0.017. The influence of equivalence ratio and fuel type on gaseous emissions of, UHC, CO and NO_x are shown from Figure 6 to Figure 8. Comparison between pure biodiesel (B100), Kerosene and blends (B20, B50) fuels regarding UHC is given in Figure 6. In this study, UHC, CO and NO_x emissions are evaluated in ppm in the exhaust gas. The UHC emissions for all fuels were reduced as the primary zone was operated richer. Generally, pure biodiesel and blend fuels (B20&B50) had slightly lower UHC emissions than kerosene in all operating conditions. However, kerosene fuel had a higher UHC than biodiesel and biodiesel blend fuels in lean conditions ($\Phi < 0.6$). Moreover, the results showed that B20 had a big impact on UHC emissions in all conditions. The reduction of biodiesel UHC emissions is due the fact that biodiesel has long carbon chains and the absence of aromatic content make cetane number higher than fossil fuels which prompt the combustion [7, 8]. Generally, the emissions of UHC for all types of fuels are low which indicated that the atomization of liquid fuels was good.

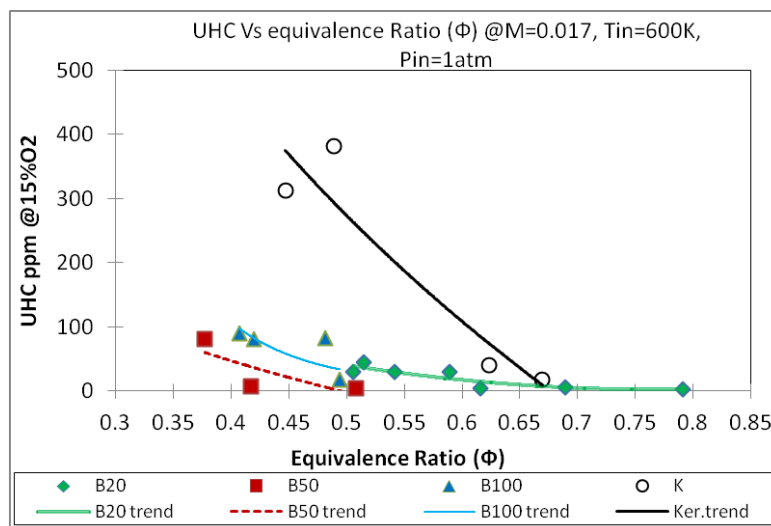


Fig.6. UHC emissions as a function of equivalence ratio for pure biodiesel, kerosene and blend.

Comparison among B20, B50, B100 and Kerosene fuels with regard CO at Mach number 0.017 and air inlet temperature 600K is given in Figure 7. The CO emissions for all fuels were reduced markedly as the primary zone was operating leaner. The range of CO emissions were almost (330-630ppm) in all type of fuels operating leaner than $\Phi=0.53$. However, the CO emissions for kerosene fuel was about 2.5 times those for B20 and about 5 times those for B100 and B20 of the mixture richer than 0.55. whereas the lowest CO emissions around 450ppm was recorded with B100 for equivalence ratio $\Phi=0.48$. The behaviour of CO & UHC emissions of biodiesel and blend fuels in gas turbine engine is in an agreements with previous studies in diesel engines [8]. Thus, characteristics of CO emissions for pure biodiesel, B50 and kerosene are similar at $\Phi=0.48$. The CO results indicated that complete combustion was achieved with biodiesel and biodiesel blend fuels which has higher oxygen content than kerosene.

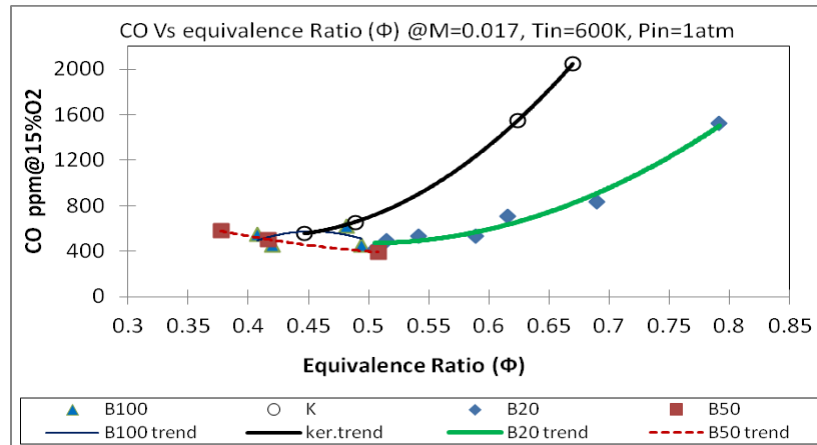


Fig.7. CO emissions as a function of equivalence ratio for pure biodiesel, kerosene and blend.

The NO_x emissions as function of equivalence ratio for biodiesel, kerosene and two blends (B20 and B50) at Much number 0.017 with an air inlet temperature of 600K were presented in Figure8. It is seen that NO_x emissions level decreases with increasing equivalence ratio for all type of fuels. B50 and B100 fuels had higher NO_x emissions than kerosene and B20 when the equivalence ratio was 0.4 to 0.5. However, NO_x emissions of B100 and B50 fuels were about 27% higher than that of B20 and their characteristics behaviour were completely identical. However, NO_x emissions increased as the concentration of biodiesel increased. This is mainly related to the oxygen content in the biodiesel and has a shorter delay time which is cause a peak pressure and temperature to enhance Nox formation. Thus, NO emissions were measured for all types of fuels and have the same trends of NO_x emissions.

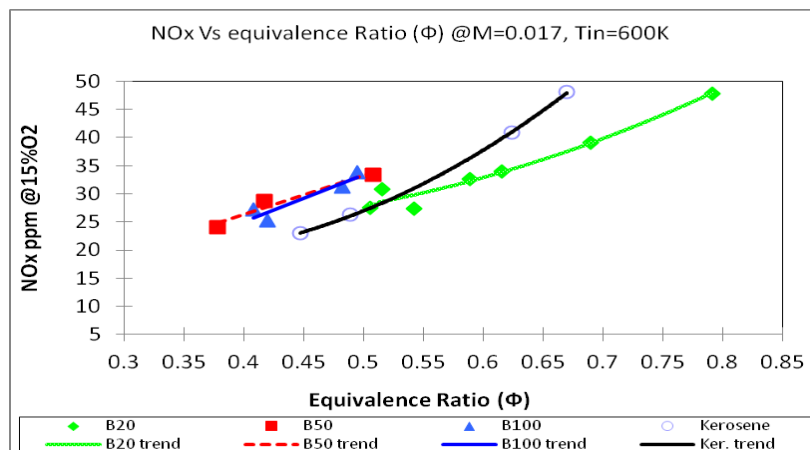


Fig.8. NO_x emissions as a function of equivalence ratio for pure biodiesel, kerosene and blend.

B. CO₂ emissions : CO₂ emissions are a direct reflection of the fuel consumption and related to fuel compositions. As the air flow is constant in the tests the CO₂ emissions increase as the equivalence ratio increases. However, the variation of CO₂ emissions was not significant between kerosene, WME and blends and CO₂ emissions were around 4.6%. The CO₂ emissions from co-firing with NG showed notable decrease due to low carbon content in NG and have a value of 4%.

C. CO₂ reductions by biodiesel comparing with fossil fuel : As described earlier, biodiesel has a lower CO, UHC emissions and renewable. It can be used in diesel engines with little or no modifications. The biggest benefit of biodiesel is theoretically carbon neutral, which means that the CO₂ emitted in the combustion of biodiesel is absorbed by plants during their growth. The net effect is therefore theoretically zero carbon emissions. However, the real net effect is not zero carbon emissions. This is due to that the production of biodiesel consumes energies and thus emits CO₂. Figure.9 shows the CO₂ reduction as a function of biodiesel fraction in blends. The maximum CO₂ reduction by biodiesel is ~80% with B100, indicating a loss of ~20% due to biodiesel's production.

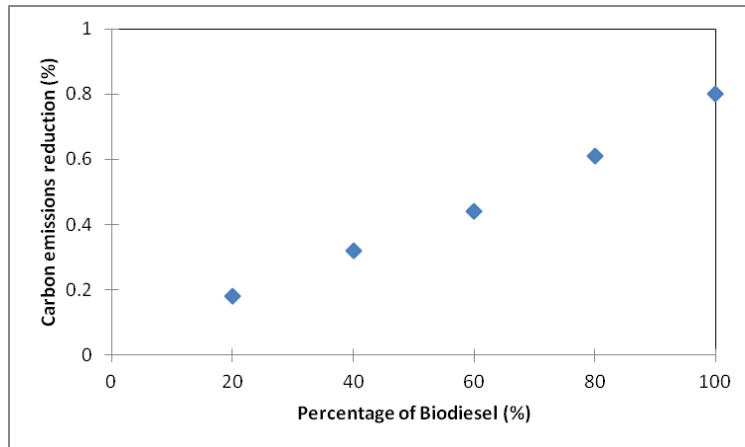


Fig.9: Effect of biodiesel blend level on CO₂ emissions[21]

The emission of CO₂ when combusting Natural gas, Kerosene and pure biodiesel are approximately (0.23, 0.26 and 0.11 kg/kWh) respectively[22]. However, based on these figures the CO₂ emissions were calculated per 100 MJ of heat energy generated for each fuel scenario and presented in Figure.10.

The emission index (EI) of Kg CO₂ per Kg fuel was calculated by multiply the calorific value of each fuel (CV) by CO₂ emission factor (EF). The EI for kerosene and NG is the CO₂ produced in a complete combustion. The EI for the WME is the CO₂ produced during its production not the CO₂ by a complete combustion. The table 2 lists the calorific value (CV), emission factor (EF) and EI of each fuel.

Table.1: Calorific value and EI for each fuel[22].

Fuel	Calorific value (CV) MJ/kg	CO ₂ emissions factor(EF)* kgCO ₂ /MJ	Emission index (EI) kgCO ₂ /kg fuel EI=CV*EF
Kerosene	44	0.93	41
Natural gas	50.1	0.82	41
Biodiesel(B100)	39.8	0.39	15.5
B50	41.9	0.66	27.6
B20	43.2	0.82	35.5

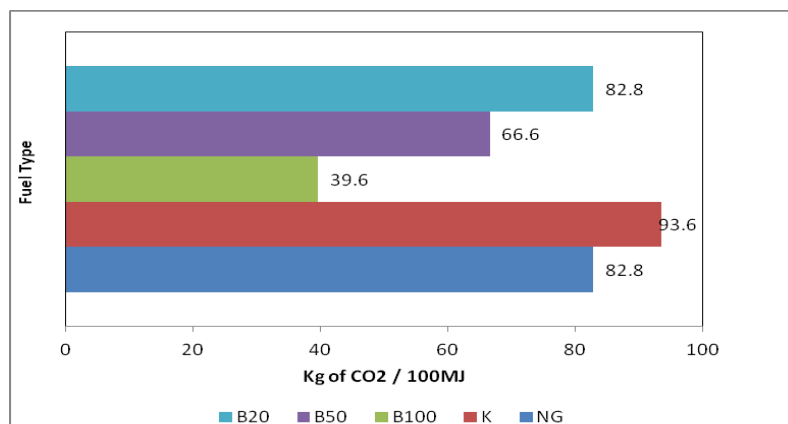


Fig.10: Average CO₂ emissions per 100MJ

Figure.10 shows the comparison among NG, Kerosene, B100, B50 and B20 fuels with regard CO₂ emitted to produce 100MJ of heat energy. It can be seen that kerosene fuel had the highest CO₂ emissions compared with pure biodiesel and its blends as well as natural gas. However, pure biodiesel had the lowest CO₂ emissions with 39.6Kg. These emissions were produced during production of biodiesel not in combustion process. Moreover, B50 produced less CO₂ emissions than B20 as the percentage of reduction increased as the concentration of biodiesel increased as shown in Figure.8.

Figure.11 shows the CO₂ emissions as a function of fuel type based on kerosene fuel to produce 100MJ of heat energy. i.e. all the CO₂ emissions were normalised to kerosene CO₂ emissions. The NG produced lower CO₂ emissions due to its higher H/C ratio. The CO₂ emissions were reduced up to ~60% for B100, 30% for B50 and 20% for B20 compared to kerosene. Also, in this study, the mass of carbon emitted to produce 100MJ of heat energy was calculated for different type of fuel and compared and presented in Figure.12. This enables a direct comparison of carbon emissions and mitigations by biodiesel compared with fossil fuels. These results can be used to estimate pollutant emissions and carbon reductions by biodiesel in power generation industry and other sectors where gas turbine engines are used.

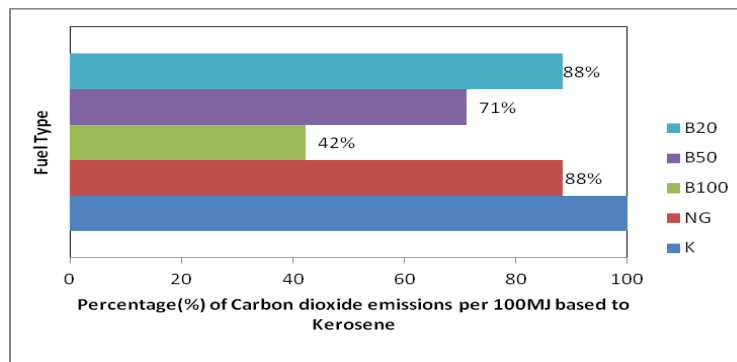


Fig.11. The Percentage (%) of Carbon dioxide emissions per 100MJ based to Kerosene

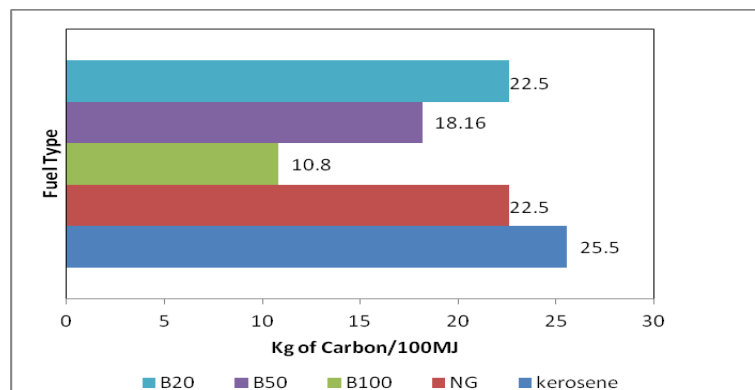


Fig.12. The average Carbon emissions per 100MJ.

III. CONCLUSIONS

In this study, combustion experiments on waste cooking oil derived methyl ester biodiesel (WME) on a radial swirler industrial low NO_x gas turbine combustor under atmospheric pressure and 600K were conducted. The principle findings are as follows:

- [1] Blends and pure fuels had much lower UHC emissions than kerosene until $\Phi=0.65$ where all fuels produced the same level of emissions.
- [2] Blends and pure biodiesel fuels produced lower CO emissions than kerosene fuel.
- [3] Pure biodiesel and its blends had higher Nox emissions than kerosene fuel.
- [4] Nox emissions of B100 and B50 fuels were higher than that of B20 and their characteristics behaviour were completely identical.
- [5] Nox emissions increased as the concentration of biodiesel increased.
- [6] The optimum conditions for WME with lowest CO, UHC and NO_x emissions were around $\Phi=0.55$.
- [7] CO₂ emissions for kerosene, pure biodiesel and blends are similar and at around 4.6%. The co-firing with NG reduced CO₂ emissions to 4%.
- [8] The replacement of fossil fuels with biodiesel can reduce carbon emissions significantly due to biodiesel's carbon neutral (or nearly neutral) characteristics.
- [9] CO₂ emissions per 100MJ of heat energy generated were reduced up to 30% for B50 and 20% for B20 and NG
- [10] There was massive reduction in CO₂ emission with pure biodiesel up to 60% compared to kerosene fuel.
- [11] From the above finding, WME is considered to be a promising alternative fuel for gas turbines

IV. NOMENCLATURE

CO: Carbon monoxide

NO_x: oxides of nitrogen

HC: Unburned hydrocarbon

NG: Natural gas

WME: Waste cooking oil Methyl Ester

FID: Flame Ionization Detector

NDIR: Non-Dispersive Infrared

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