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INFLUENCE OF RESIDENCE TIME ON FUEL SPRAY SAUTER MEAN DIAMETER (SMD) AND EMISSIONS USING BIODIESEL AND ITS BLENDS IN A LOW NOX GAS TURBINE COMBUSTOR

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ABSTRACT

Biodiesels have advantages of low carbon footprint, reduced toxic emissions, improved energy supply security and sustainability and therefore attracted attentions in both industrial and aero gas turbines sectors. Industrial gas turbine applications are more practical biodiesels due to low temperature waxing and flow problems at altitude for aero gas turbine applications. This paper investigated the use of biodiesels in a low NOx radial swirler, as used in some industrial low NOx gas turbines. A waste cooking oil derived methyl ester biodiesel (WME) was tested on a radial swirler industrial low NOx gas turbine combustor under atmospheric pressure, 600K air inlet temperature and reference Mach number of 0.017&0.023. The pure WME, its blends with kerosene (B20 and B50) and pure kerosene were tested for gaseous emissions and lean extinction as a function of equivalence ratio for both Mach numbers. Sauter Mean Diameter (SMD) of the fuel spray droplets was calculated. The results showed that the WME and its blends had lower CO, UHC emissions and higher NOx emissions than the kerosene. The weak extinction limits were determined for all fuels and B100 has the lowest value. The higher air velocity (at Mach=0.023) resulted in smaller SMDs which improved the mixing and atomizing of fuels and thus led to reductions in NOx emissions.

INTRODUCTION

Issues with energy supply security and concerns over climate change have accelerated the research and development of alternative fuels. Blending of biofuels such as biodiesel and bioethanol with petroleum derived fuel has become a popular practice due to the need to reduce CO_2 emissions and concerns over depleting oil reserves in road transport. EU directive 2003/30/EC launched a scheme to promote the use of biofuels in transport [1]. European fuel quality standards allow a B7 mix; i.e. 7% biodiesel, to be mixed with petroleum diesel without invalidating manufacturers warranties.

Biodiesel (FAME) has slightly higher viscosity to diesel fuels and is able to be used directly in diesel engines. It offers reduced toxicity including lower particulate emissions and absence of sulphur compounds.

The application of biodiesel in gas turbine engines has been developing and yet still much less extensive compared to diesel engines. The use of biodiesels in aero gas turbines has be constrained due to the poor low temperature flow properties. The jet fuel standard (D1655-09,13) classified FAME as a contaminant in the jet fuel delivery systems [2]. The biofuels for aero gas turbine engines need to be drop-in fuels that are completely compatible with the existing engines and fuel storage and delivery infrastructure. So the application of biodiesel in gas turbines turned into industrial gas turbine engines. There has been some work reporting the biodiesel tests on the small and micro gas turbine engines [3-5] and heavy duty gas turbine

engines [6, 7]. They found that NOx emissions from biodiesel were in a comparable level and engine cold start could be an issue. Liu etc [8] reported a biodiesel testing program on industrial gas turbines that the pure biodiesel (B100) derived from waste cooking oil was tested on the atmospheric and pressure testing rigs in the SGT-100 DLE combustion system to investigate ignition, emission and combustion dynamics using. They found that the biodiesel was easier to ignite at high air mass flow rates and harder at lower flow rates and the lean extinction limits had similar trends as well. The emissions results from pressure rig they derived showed that biodiesel had lower NOx and CO emissions than diesel and comparable UHC emissions with diesel.

The work in this paper is the continuation of a previous work by authors [9], in which the authors compared emissions between a waste cooking oil derived methyl ester (WME) and kerosene including co-firing with natural gas using a radial swirler industrial low NOx gas turbine combustor under atmospheric pressure and 600K preheated air at Mach number of 0.017. The purpose of this paper is to expand the emissions to Mach number 0.023 and link emissions with Sauter Mean Diameter (SMD) of droplet sizes for the pure WME (B100), its blends with kerosene (B20 and B50) and pure kerosene.

EXPERIMENTAL SET UP

Combustion Rig

The combustion test facility consisted of an air supply fan, venturi flow metering, electrical preheaters, 250mm diameter air plenum chamber, 76mm outlet diameter double passage radial swirler, 76mm diameter throat 40mm long wall fuel injector, 330mm long 140mm diameter uncooled combustor followed by a bend in the water cooled exhaust pipe with an observation window on the combustor centre line. This was used in the weak extinction tests and in observing the flame shape.

The 76mm radial swirler assembly with two co-rotating radial swirlers is shown in Figs.1 and 2 [10]. The two swirlers were separated by a splitter plate with a 40mm diameter outlet orifice, as shown in Fig. 3. The vane passage shape is also shown in Fig.3 and had a rounded entry and tapered vane shapes, as used commercially by Willis et al [11] in a counter-swirl configuration. The 40mm splitter plate between the two 76mm outlet radial swirlers was to try to create a separation of the upstream swirler air flow to give a better flame stability with the central injector injection.

The swirler outlet throat was 76mm diameter and 40mm long and 8 equispaced fuel injection orifices were mounted in the wall of the swirler outlet throat. This throat was in place for the vane passage fuel injection as well as the wall fuel injection tests. The wall injector for natural gas fuel had eight equispaced 3mm diameter holes, located 20mm from the throat inlet and inclined 30° towards the upstream flow. For liquid fuels, the central radial fuel injection was from a hole pointing radially outwards from the combustor centreline, around 2mm from the

swirler backplate. The injection hole size was 2.2mm diameter and the fuel spoke were 13 mm outer diameter.

The test conditions were designed to achieve two references isothermal Mach numbers (0.017&0.023) at 600K in the 140mm diameter combustor at atmospheric pressure. The first Mach number typically represents ~40% of the total combustor airflow entering the lean primary zone through the radial swirler. Also, this Mach number represents a lower power simulation of an air staged combustor or combustor with air bleed or IGV air throttling. Whereas Mach number of 0.023 represents ~75% of the total combustor airflow entering the lean primary zone through the radial swirler. The inlet temperature was measured 100mm upstream of the swirler using chrome-alumel type K thermocouple. The ignition was carried out by electrical discharge from the spark igniters. The higher Mach number (0.023) enabled the pressure loss to be increased from 1.5% at Ma=0.017 to 2.7% at Ma=0.023.

Fuels

Kerosene was stored in a 200 litre barrel whereas the 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 a rotameter 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. The fuel properties for kerosene and WME are shown in Table 1.

Table1: Fuel properties

Property	Fuel	
	Kerosene	Biodiesel
Density at 25°C(Kg/m3)	800	884
Viscosity at 25°C(mm2/s)	1.71	5.61
Surface tension at 25°C		31.1
Calorific value (MJ/Kg)	46	39.8
Carbon %	85	75
Hydrogen %	15	11
Oxygen %	0	14

Ignition of the methane-air used a high energy spark mounted at the shear layer impingement point 50mm downstream of the swirler throat exit. The liquid fuel flow rate was gradually increased to attain the desired equivalence ratio, while the methane flow rate was slowly decreased to zero. Liquid fuels (B100, B50, B20 and Kerosene) were injected through the central injector and mixed with incoming air. The air fuel ratio (equivalence ratio) was increased in small steps by increasing fuel flow rate whilst keeping air flow rate constant.
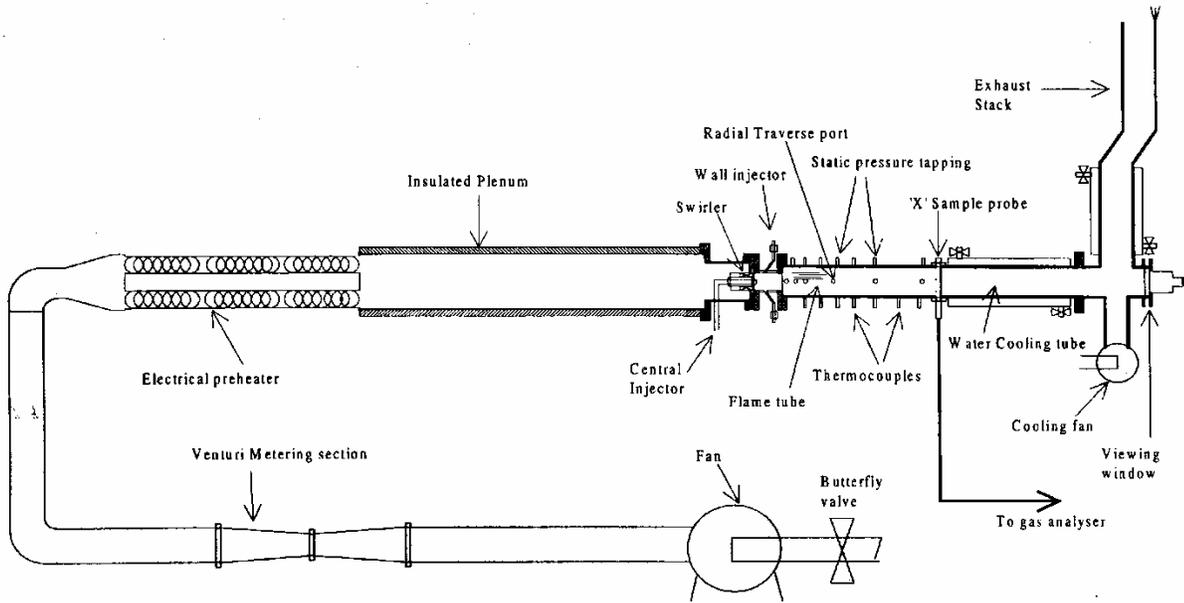
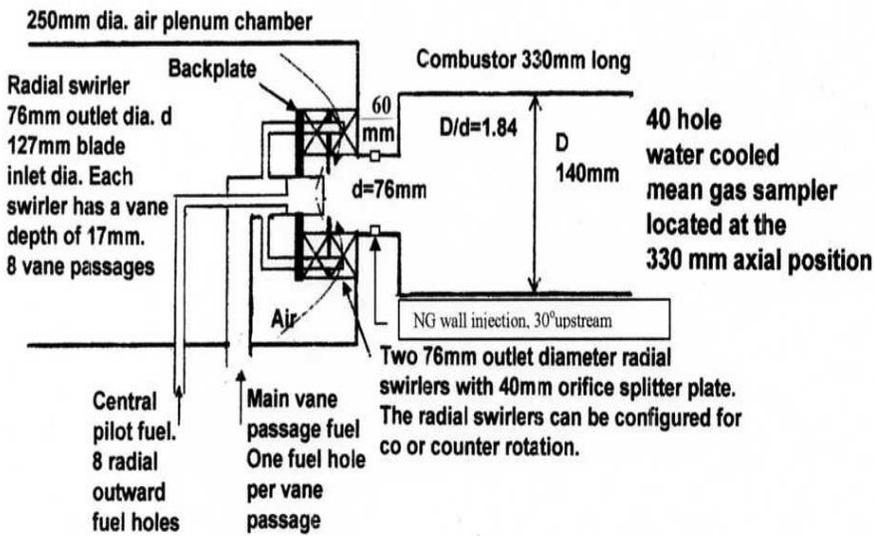Figure 1: Overall set up of the combustor rig

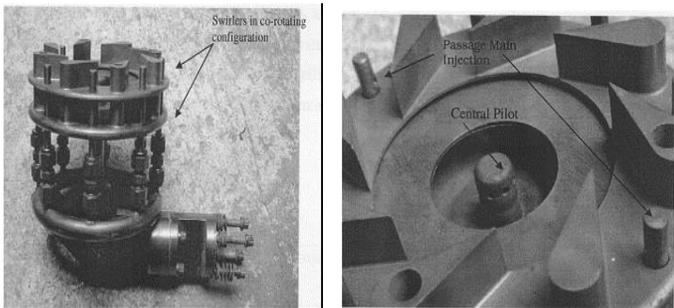Figure 2: Combustor geometry

Figure 3: The co-rotating radial swirler assembly with central and radial passage fuel injection

Emissions measurement

Mean exhaust gas samples were obtained using an 'X' configuration stainless steel water cooled probe with 40 holes at centers of equal area. The sample gases were passed into a 190^0C heated sample line and on through a 190^0C heated filter and pump to a 190^0C heated gas analysis system. The gas analyses results were processed to provide air fuel ratio, combustion efficiency and mean adiabatic flame temperature. The NOx emissions were measured hot on a wet gas basis using a chemiluminescence NOx analyzer (Signal Instruments, UK) with vacuum ozone reaction chamber. This measured NO_2 by the difference in total NOx and NO, using a carbon molybdenum converter to oxidize NO_2 to NO at 400^oC. It had a minimum scale of 1-4ppm with a 0.05ppm resolution. The total unburned hydrocarbons were measured using a heated FID. The CO and CO_2 were measured on a dry gas basis using NDIR with Luft cell detectors (ADC). All emissions were corrected to 15% O_2.

RESULTS AND DISCUSSIONS

Influence of Biofuel Injection Location

Initially it had been thought that the WME would burn satisfactorily with vane passage fuel injection. This was attempted with central ignition of natural gas, but no cross light could be achieved and no flame could be stabilized with the WME with this fuel injection location. The other fuel injection location that had demonstrated low NOx with natural gas was at the outlet throat wall. This was also investigated and again no cross light from a central natural gas flame could be achieved. Thus the two positions for fuel injection that gave low NOx with gaseous fuels would not stabilize a flame with the WME. Kerosene could be burned satisfactorily with low NOx when injected at these locations [10]**.** The reason for this was that the air inlet temperature of 600K was too low to vaporize the WME, whereas with kerosene the much lower distillation range led to easy vaporization.

The only fuel injection location where WME flames could be stabilized was the central injector. This had been shown in early work with radial swirlers, with no downstream outlet throat and a small depth radial swirler to have very low NOx characteristics on kerosene [10, 12]. However, the addition of the discharge throat in the present work did not perform as expected and the fuel and air mixing was not as good as without the throat and the NOx was higher for kerosene. The reason was thought to be that the mixing occurred in the downstream shear zone in the expansion flow, shown in Fig. 1. The addition of the throat makes the central fuel injector remote from the shear layer mixing region. For the WME the negligible vaporization would occur in the exit throat at 600K. The main fuel vaporization route was through central recirculation of hot burned gases that recirculate back to the head of the radial swirler, where the liquid fuel was injected. This was why B100 WME could be burned without natural gas assistance, whereas for vane passage or outlet wall fuel injection no flame could stabilize, as there was no hot gas recirculation in these regions.

Weak Extinction Limit (WEL)

The weak extinction was determined by igniting the flame with natural gas vane passage injection and then turning off the natural gas once the combustor was hot. The fuel flow to the central injector was then gradually reduced at a constant air flow until no flame was observed through the air cooled observation window mounted on the centre line of the combustor in a 90° bend in the exhaust. The weak extinction was also accompanied by a sudden increase in hydrocarbon emissions. Table 3 presents the weak extinction limit (WEL) for all fuels that have been tested. Biodiesel fuel with and without co-firing and its blend (B50, B20) established lower lean extinction limit compared to kerosene due to the oxygen content in the fuel.

Table 2: Weak extinction limit for kerosene and WME and their blends at Mach numbers of 0.017 & 0.0225, inlet temperature 600K, 1 atm.

	Weak extinction(Ø)		Maximum phi at onset of acoustic resonance		Maximum Phi at white smoke	
Mach No.	**0.017**	**0.023**	**0.017**	**0.023**	**0.017**	**0.023**
Kerosene	0.46	0.62	0.66	0.93	…….	…
B20	0.44	0.56	….	…	0.76	0.79
B50	0.36	0.47	….	….	0.5	0.66
B100	0.35	0.28	……	……	0.5	0.49

The weak extinction results in Table 2 were unexpected, as the WME B100 and its blends with kerosene had lower WEL than pure kerosene at both Mach numbers. This could be due to oxygen content in the WME, which would aid flame stability but at the expense of the increased NOx shown later. The influence of Mach number was also not expected, particularly the large reduction in the kerosene weak extinction at the higher M (Φ was increased from 0.46 to 0.62) and in contrast to an improvement in the B100 WME weak extinction (Φ was reduced from 0.35 to 0.28). The smoke results for B100 indicated a deterioration in fuel air mixing, in spite of the lower SMD at the higher M. Improved atomization at the higher Mach number should result in better mixing but the B100 smoke result did not behave as expected. The deterioration in the weak extinction for kerosene at the higher M was also difficult to explain as a weak extinction closer to the fundamental flammability limit is expected and this is 0.4 Φ, close to the weak extinction at the lower M. It is considered that the central fuel injection with a large radial swirler vane passage depth, coupled with a relatively long exit throat, resulted in the fuel placement resulting in the shear layer high turbulence regions not being the main stabilization zone. The flame may stabilize further upstream in the throat where velocities were higher and flame stability was lower.

Also shown in table 2 is the practical phenomenon of white smoke. Although the combustion was enclosed, it was an atmospheric pressure test and at a particular equivalence ratio white smoke started to leak from the joints in the test rig and filled the room. Operating at the richer mixtures was then unsafe and the combustor had to shut down. A further feature of low NOx combustion was the onset of acoustic resonance. This can limit the Φ that can be operated as acoustic resonance cannot be tolerated in the test facility. There was no problem with acoustic resonance with WME blends but there was with kerosene. At the lower M the onset of acoustic resonance was at Φ=0.66, close to the desired operating range. However, at the higher M acoustic resonance was not reached until Φ=0.93. Resonance is a coincidence of chemical and acoustic time constants in the combustor. Changing the Mach number increases the flow velocities and creates more turbulence and this changes the chemical time constant. This then enabled much richer mixtures to be operated without resonance.

Sauter Mean Diameter (SMD) Calculation

Sauter Mean Diameter (SMD) of the droplet size is defined as the ratio of the volume to surface area and usually used to characterize the drop penetration and heat and mass transfer. The SMD in the present work was calculated and compared for all fuels according to the Lefebvre equation [13, 14] for air blast atomization.

$$SMD = 1 \times 10E - 3 * \left[\frac{\sqrt{\sigma \rho L}}{\rho A V A} \right] * \left(1 + \frac{1}{AFR} \right)^{0.5} + 6 \times 10E - 5 \left[\frac{\mu L^2}{\sigma \rho A} \right]^{0.425}$$

$$\left(1 + \frac{1}{AFR} \right)^{0.5}$$

Where:
SMD: Sauter mean diameter   (m)
AFR: air fuel ratio
VA: air velocity   (m/s)
μL: fuel viscosity   (m²/s)
ρA: air density   (kg/m³)
ρL: fuel density   (kg/m³)
σ: surface tension

The SMD for kerosene and pure biodiesel were calculated and compared at Mach numbers 0.017 and 0.023 as shown in Fig.4. This shows that for Mach=0.017 biodiesel had a larger (x 1.27) droplet size than kerosene at the same conditions. Biodiesel has a higher viscosity compared to kerosene fuels and this increases the droplet size. Fig.4 also shows that at the higher Mach number of 0.023 used in the present work, the higher air velocities reduced the SMD. At the higher Mach number the WME had a SMD that was a little lower than for kerosene at Mach=0.017. The SMD of kerosene decreased from 44 to 36 μm

compared to a decrease of 57 to 46 μm for the WME as Mach number increased from 0.017 to 0.023. However, all the droplet sizes were in the range of below 70 μm where kerosene sprays burn like gaseous fuels.

Liu et al [8] measured and compared the droplet size of biodiesel and diesel fuels. They concluded that biodiesel had larger droplet size than diesel fuel at the same conditions. Also their results showed that besides fuel properties, atomization and fuel-air mixing process had a big impact on emissions especially NOx. Their results were in a good agreement with this work as the inlet air velocity increased, the mixing and atomizing of fuels was improved and thus the NOx emissions decreased at the higher Mach number.
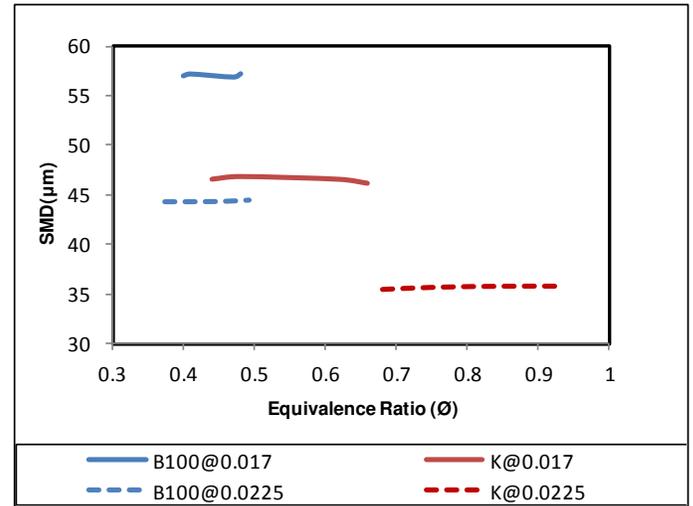

Figure 4: SMD comparison for both fuels at reference Mach numbers of 0.017 and 0.023

Effect of Mach Number on Emissions

The emissions results for kerosene and B20, B50, B100 WME measured in this study are compared for both Mach number 0.017 and 0.023 with the same flame stabilizer and 600K air inlet temperatures. The results are plotted in Figs. 4-9 as a function of the equivalence ratio for 600K inlet temperature and both Mach numbers 0.017 and 0.023. The higher reference Mach number was undertaken to gain a more realistic pressure loss, which would improve the atomisation.

NOx emissions

The influence of Mach number on NOx emissions is shown in Figs. 5&6. At Φ=0.7 the kerosene results showed a large reduction in NOx at the higher Mach number with reduced residence time and higher pressure loss. This indicated the influence of improved mixing with a higher pressure loss. At this equivalence ratio thermal NOx is important, which was reduced when the mixing was improved. For B100 the only common

equivalence ratio is for Φ=0.5 (~1750K) and this also showed lower NOx at the higher Mach number, but the change was much smaller than that for kerosene at Φ=0.7. At the lower Φ the flame temperatures were outside the thermal NOx formation range which was why the influence of Mach number on NOx was smaller. Fig.6 shows the influence of Mach number on NOx for B20 and B50. In both cases at the same Φ the higher Mach number reduced the NOx, indicating a reduction in thermal NOx formation due to the shorter residence time and better mixing at the higher pressure loss at the higher Mach number operation.

CO Emissions

The CO emissions as function of equivalence ratio are shown in Figs. 7&8. Comparison of kerosene with the B100 WME in Fig. 7 shows little influence of Mach number on CO emissions for the same Φ. There is some evidence of higher CO with B100 at Φ=0.4 at the higher Mach number. This could be due to the reduced residence time at the higher Mach number for CO oxidation. For B20 and B50 blends, the Mach number had a significant influence on CO emissions as shown in Fig. 8. The B50 results only had one pair of data for both Mach numbers, i.e. Φ ≈ 0.5, where CO concentrations were doubled at the higher Mach number. CO concentrations were at least doubled for B20 at the higher Mach number.
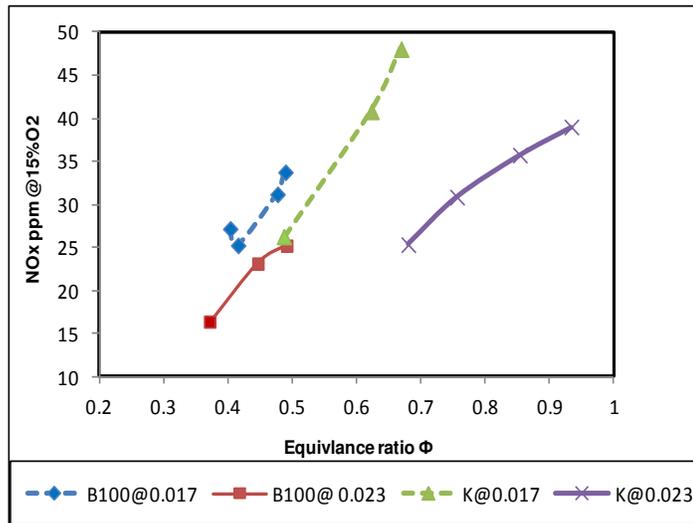

Figure 5: Comparison of NOx emissions for B100 & kerosene at different Mach number
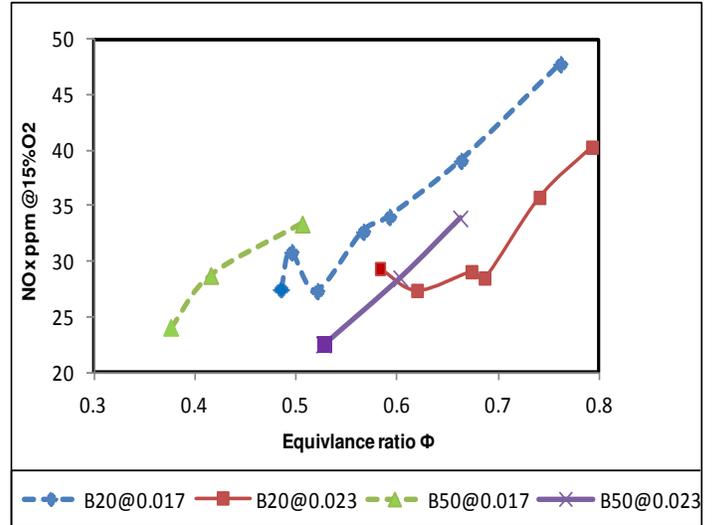

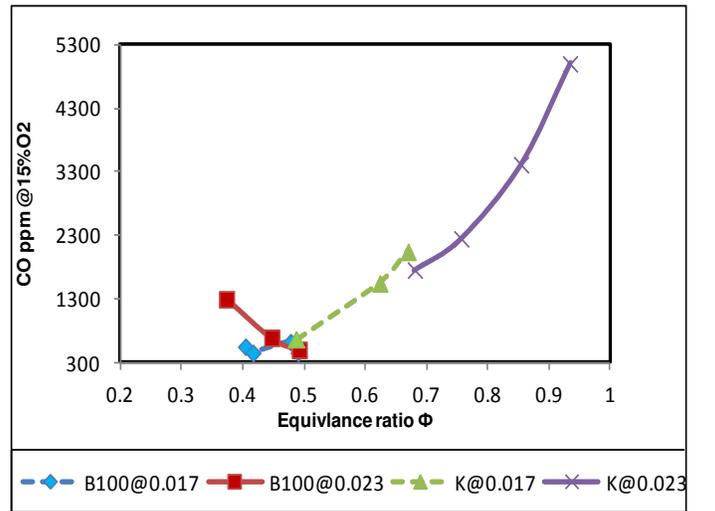Figure 6: Comparison of NOx emissions for B20 & B50 at different Mach number

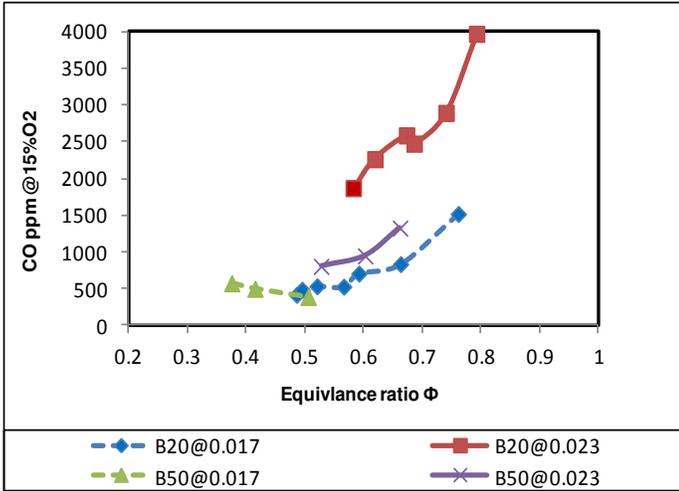Figure 7: Comparison of CO emissions for B100 & kerosene at different Mach number

Figure 8: Comparison of CO emissions for B20 & B50 at different Mach number.

UHC Emissions

Comparison of UHC emissions between the two Mach numbers for pure biodiesel (B100) and blends (B20, B50) fuels are shown in Figs 9&10. The results show that the emissions of UHC increased at the higher Mach number due to the reduced residence time. The results also show that UHC concentrations were lower with the WME compared to kerosene at the same equivalence ratio (for example, Φ=0.5 and Ma=0.017 in Figs 9 & 10, B20 Ma=0.017 Vs kerosene Ma=0.017). This demonstrated that in spite the WME had higher boiling point and was more viscous than the kerosene, the UHC emissions were not adversely affected. This was attributed to the oxygen content in the WME that assisted the combustion and oxidation of the hydrocarbons.

It was difficult to compare emissions at wider equivalence ratio ranges where the comparisons could be made at the same equivalence ratio for either the different Mach number or different fuels due to the difference in weak extinction limits.
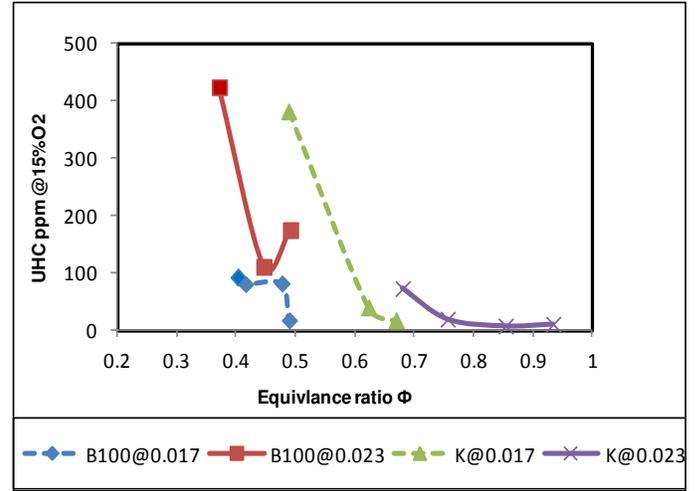

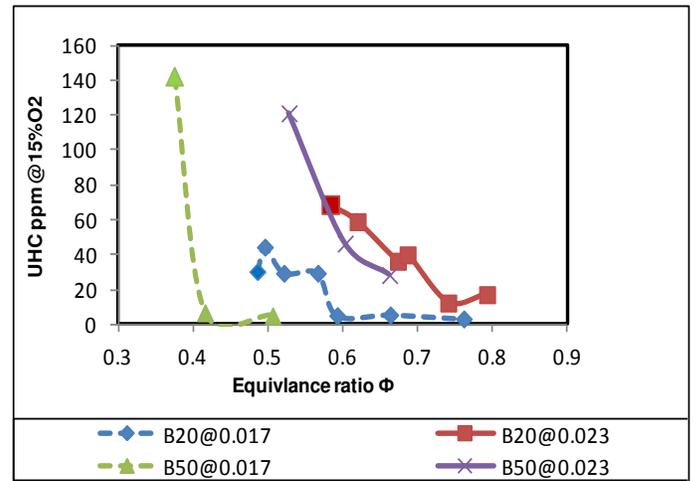Figure 9: Comparison of UHC emissions for B100 & kerosene at different Mach number

Figure 10: Comparison of UHC emissions for B20 & B50 at different Mach number

CONCLUSIONS

In this work, combustion experiments were conducted using waste cooking oil derived methyl ester biodiesel (WME) and its blends with kerosene on a radial swirler industrial low NOx gas turbine combustor under atmospheric pressure and 600K. The tests were carried out at inlet air velocity of Mach number 0.017 and 0.023 respectively. The main findings are as follows:

1) The WME and its blends (B50, B20) had lower CO, UHC emissions and higher NOx emissions than the kerosene.
2) As the Mach number increased or residence time reduced, the NOx emissions decreased for all fuels.
3) CO and UHC emissions increased as the Mach number increased for all fuels due to the shorter residence time and thus less oxidation of CO and UHC.
4) Biodiesel has larger droplet sizes than kerosene at the same conditions. The big difference in the droplet size of both fuels

is due to dynamic viscosity. As the Mach number increased, the SMD of fuel spray droplet size was reduced significantly, indicating improved fuel air mixing.

ACKNOWLEDGMENTS

NOMENCLATURE

CO: Carbon monoxide.
CFD: computational fluid dynamic
FAME: Fatty Acid Methyl Ester.
FID: Flame Ionization Detector.
NOx: Nitric Oxides.
NG: Natural Gas.
NDIR: Non-Dispersive Infrared.
UHC: Unburned Hydrocarbon.
WME: Waste cooking oil Methyl Ester.

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