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Combustion and emission performance of CO2/CH4/biodiesel and CO2/CH4/diesel blends in a Swirl Burner Generator

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Abstract

Renewable biomass derived fuels are of increasing attention for industrial and aerospace applications due to worldwide depletion of fossil fuels and stricter environmental legislations. These facts have prompted continuous development for clean, sustainable and alternative fuels that produce low emissions. Even more, fuel flexibility is a required feature to meet all the former characteristics while reducing operating cost in gas turbines. Thus, some alternative fuels such as syngas or biodiesel can be used for gas turbines as these can comply with these requirements while being obtained from various processes, making them potential candidates for sustainable power generation. On the other hand in many combustion applications, the fuel is originally present as either liquid or solid. To assist mixing and the overall burning rate, the fuel is frequently first atomised and then sprayed into the combustion chamber. Most of the existing approaches dealing with combustion flows are limited to single-phase injection. To remove this limit, a new model for multiphase combustion has been developed. Therefore, this experimental work investigated the performance of a swirl burner using various mixtures of CO2/CH4 blends with either diesel or biodiesel derived from cooking oil. A 20 kW swirl burner was employed to analyse gas turbine combustion features under atmospheric conditions to quantify flame stability and emissions by using these fuels. A TESTO 350XL gas analyser was used to determine NOx and CO emission trends. Comparison between the blends was carried out at different equivalence ratios. CH* chemiluminescence diagnostics was also used and linked with the levels of emissions created through the trials. The results revealed that the use of biodiesel and CO2/CH4 blends mixtures resulted in lower CO production, i.e. 87% lower for the case at 10% CO2. Results showed that a notable reduction of ~50% in NOx was obtained at all conditions for the biodiesel /CO2/CH4 blends. Diesel based flames showed high CH* intensity at the axial profile compared to the biodiesel blends due to their high sooting tendency.

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Keywords: ***Two-phase flow, Biodiesel, combustion, Gas Turbine, emissions, heat release***

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1. Introduction

Studying multiphase combustion is vital because at this time a very high percentage (80%) of energy is produced by combustion of liquids such as gasoline, solids such as coal, and gases such as natural gas. For instance, during the first decades of the twenty-first century, more than 50% of the electricity was generated by coal-fired furnaces in the United States [1]. On the other hand, to decrease pollutants means to decrease maximum flame temperature and to decrease the size of fuel-rich regions where fuel rich concentration and high-temperature gradients can arise. To complete these aims a deep knowledge of multiphase flow processes, spray dynamics, and the interface between the liquid and gas phase is essential [2, 3]. The resultant multi-phase flows are very complex processes that include turbulence, mass and heat transfer, droplet dynamics and phase changes that are strongly connected. There is an ever-increasing need to understand multiphase combustion because of its wide application in energy, transportation, environment, propulsion, industrial safety, and nanotechnology [4, 5]. Different modelling methods currently exist for multiphase flows such as Eulerian-Lagrangian, Eulerian Multiphase, Volume of Fluid (VOF), etc. The most commonly used are the Eulerian-Lagrangian method [6, 7]. This approach has been controlled in guessing the behaviour of sprays. Although many researchers and engineers have used the Lagrangian-Eulerian formulation as a numerical simulation tool for an estimate of characteristics of complex multiphase flows to guide their engineering devices design, the concept and application have severe limits [6-8].

Regarding alternative fuels, the requirement to meet stringent environmental legislation and emissions target has prompted continuous development for sustainable, clean, alternative fuel and low-emissions combustion technology. In the field of the gas turbine, fuel flexibility is a required feature from the standpoint of meeting emission objectives and reducing operating cost. One of the prospective alternative fuel for a gas turbine is biodiesel. Fundamental combustion characteristics and performance of biodiesel has been studied using model gas turbine burner by several groups. Chong and Hochgreb [9] compared the spray combustion properties of palm biodiesel with baseline fuels of Jet-A1 and diesel using a model gas turbine burner. The result shows that NOx emission was reduced in the case of palm biodiesel, while CO emission was not affected. H. Kurji et al. investigated a comparison among three fuels, kerosene and a biofuel in unsaturated and saturated form. The fuels were tested to compare the relative performance of the saturated biodiesel for gas turbine applications. It was observed that use of the saturated blend would result in higher NOx concentrations in the exhaust with less oxygen and CO emissions. It has been shown that the ideal operability region for the saturated biodiesel is at very lean conditions[10]. Regarding alternative fuels, the main goal of introducing CO2 into the gas turbine combustor is the reduction of NOx emissions, that is completed by cooling the flame [11]. Lee et al. [12] essentially examined the influence of diluting the premix fuel on the emission of NOx and CO from a model gas turbine. They showed that reducing NOx per unit power is logarithmically associated to the heat capacity of the total diluent added. Since carbon dioxide has a maximum heat capacity than steam or nitrogen, a smaller mass flow rate is necessary for a comparable reduction in NOx. H. Kurji et al. carried out an experimental study on the combustion of methane-carbon dioxide mixtures at atmospheric conditions by using different levels of premixing with different injection strategies. Results were showed that the introduction of limited amounts of CO2 (15%) had controlled reaction rates and temperatures in the combustion zone, thus causing a reduction in emissions with a decrease in flame stability at low equivalence ratios[13].

Therefore, the present work has been focused on that Multi-phase studies by using a swirl burner. An experimental study on the combustion of CO2/CH4/Diesel vs CO2/CH4/ biodiesel mixtures at atmospheric conditions where the biodiesel derived from cooking oil. A 20 kW swirl burner was employed to analyse gas turbine combustion features under atmospheric conditions to quantify flame stability and emissions by using these fuels. The burner configuration consisted of a centre body with an annular, premixed gas/air jet introduced through five, 60° swirl vanes. A TESTO 350XL gas analyser was used to determine NOx and CO emission trends. Comparison between the blends was carried out at different equivalence ratios. CH* chemiluminescence diagnostics was likewise used and correlated with the levels of emissions produced during the trials at different flow rates. The resulting images were analysed using MATLAB R2016a and Photron FASTCAM PFV Ver.3670 software and to determine instability patters that were correlated to fuel blend.

2. Experimental

An axial swirling flame burner was utilised to establish continuous premixed swirling flames at atmospheric conditions. This swirl injector consists of a liquid inlet, gas inlet, aeration tube, mixing chamber, swirl-generating vanes, swirl chamber, and the discharge orifice. The schematic of the swirl burner and the placement position of swirler are shown in Figures 1. The liquid flows were supplied independently to the atomiser through the centre via a central injector, whereas premixed gas was supplied through the outer injector with a low velocity for the purpose of getting good mixing with the liquid stream at the mouth burner. The air-gas mixture passes through swirl-generating vanes which create swirling effects on the mixture before exiting the injector through the discharge orifice. Low liquid flow-rate was intended in this study to simulate low fuel consumption and to get better atomisation compatible with the velocity of the premixed gas. There are several parameters to take into consideration such as; the diameters of the chambers, the diameter of the exit orifice and air injection hole size, quantity and location [14, 15]. Literature has shown, depending on the parameters chosen for the design, the air to liquid ratio (ALR) and the pressures at which the fluids are supplied. The ALR appears to have a particularly large effects on the mean droplet size; higher ALR tends to result in smaller mean droplet sizes. The schematic of the swirl flame burner and the flow delivery system is shown in Figure. 2.

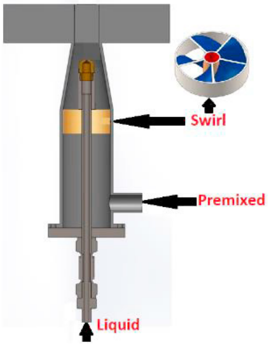

Figure 1. Schematic burner with swirler position and Axial swirler.

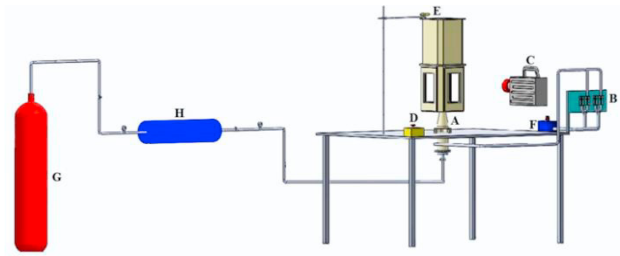

Figure 2. Generic swirl burner with Accessories. A - Swirl Burner; B – Rotameters; C – High-Speed Camera; D – Emergency button; E – Pilot Burners; F – Air Regulator; G- Nitrogen Cylinder; H-Accumulator.

A Delavan 0.4 x 60 A, nozzle atomiser was used as the fuel injector to atomise liquid fuel before mixing with swirling premixed. The atomiser nozzle was placed as shown in Figure 1 to spray the fuel at operating pressures of 5 bar absolutes at 0.54 litre/hour constant flow rate using compressed nitrogen, passing into a liquid accumulator, as shown in Figure 2. The swirl burner used in this trials consists of an axial swirler and a circular stainless steel tube placed as shown in Figure 1. Gases and air were premixed in separate tubes to ensure adequate mixing before entering the burner. A pilot ignitor was used to ignite the flame, the combustion chamber is of rectangular form and has four internal quartz windows. Giving full optical access to the combustion, the width and the height of the combustion chamber is 118 mm and 410 mm respectively. More details of the burner geometry are shown at [13].

Table 1.blend mixtures composition (vol. %)

Mixture	CH_4	CO_2	Liquid Fuel		Mixture	CH_4	CO_2	Liquid Fuel
B1	100	0	Diesel		B4	100	0	Biodiesel
B2	95	5	Diesel		B5	95	5	Biodiesel
B3	90	10	Diesel		B6	90	10	Biodiesel

Table 1 shows all tested blends. The effect of CO2 as diluent on the emissions has been studied by incrementally adding CO2 from 0%, 5% and 10%. The blends for all cases were supplied by cylinders that contained CO2 already mixed with CH4 at the required percentages. Various blends were tried to observe how the increment of CO2 in the blends affected the flame and reduce/increase NOx and CO emissions. A Photron Fastcam APX-RS high-speed camera operating at 300 frames/s was also used with a 105 mm, 1:2.8 Nikon lens. The resultant images were analysed using Photron FASTCAM PFV Ver.3670 software and MATLAB R2016a.

3. Results and discussion

3.1. Exhaust gas analysis

Comparison of the NOx emissions for CO2/CH4/biodiesel and CO2/CH4 /diesel under various equivalence ratios is shown in Figure 3. Overall, emissions of NOx from all fuels decreases almost linearly with the increase of excess air ratio. Lower NOx are produced at extreme high excess air ratios due to the lower flame temperature that suppresses the formation of thermal NOx [16]. Biodiesel blends show lower NOx emissions compared to diesel blends for all the cases and different equivalence ratios. The trend of lower NOx emissions for Biodiesel could be due to the role of oxygen in the molecule that suppresses CH production, thus reducing prompt NOx formation [17, 18]. Moreover, the lower NOx values must be attributed in part to the higher heat of vaporisation of the Biodiesel spray. Regarding CO2 dilution, overall, all tested equivalence ratio showed a decreasing trend as the CO2 diluent ratio increases for both types of liquids. The lower NOx can be attributed to the thermal effects of CO2 diluents. The thermal effect decreases the flame temperature and thus the thermal NOx [19]. CO2 diluent reduces the adiabatic temperature due to higher specific heat, which would result in a significant decrease in overall burning rate [20]. This is a consequence of the cooling of the flame by absorbing heat from the combustion process due to the high specific heat of the molecule. Lowering the flame temperature caused less NOx to be emitted, concurring with the thermal NOx formation mechanism [19]. The addition of diluent to the air stream also causes a corresponding decrease in oxygen mole fraction. Consequently, the flame temperature and the mole fractions of H, O, and OH radicals reduce. For the chemical effect, the addition of diluents may decrease the N and HCN mole fractions and subsequently reduces prompt NO [21]. According to the extended Zeldovich mechanism [19], as flame temperatures increase so do emissions of nitrous oxides, with reaction rates determined experimentally with reasonable accuracy [9]. Case B5 and B6 show significant lower NOx emissions. Results show the effect of biodiesel and CO2 dilution on the NOx emissions, with a considerable impact. Using biodiesel and 10% CO2 resulted in the average decrease of NOx by ~50% compared with B1 for equivalence ratios =1.6, as shown in Figure 3.

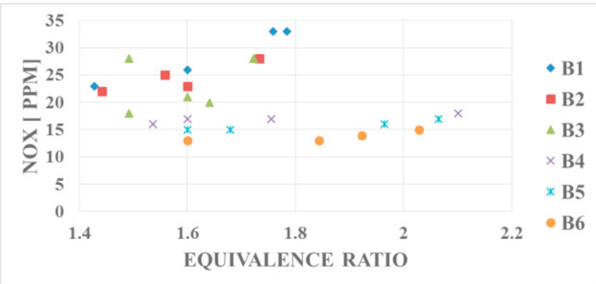

Figure 3. NOx exhaust gas concentration (dry) as a function of equivalence ratio for all different blends.

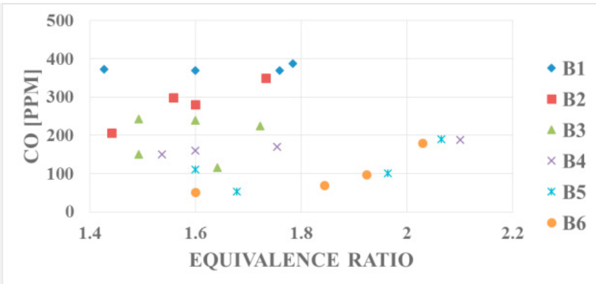

Figure 4. CO exhaust gas concentration (dry) as a function of equivalence ratio for all different blends.

The emissions index presented for CO as a function of equivalence ratios is shown in Figure 4 for all mixtures. CO emissions are influenced by the equivalence ratio and fuel blend at different operating conditions. Overall, emissions of CO for all fuels decreases with the increase of excess air ratio. CO emissions are higher for low excess air ratios as too many rich pockets survive. For high excess ratios, the temperatures are very low, and any CO formed in rich spray pockets are quenched by the low-temperature mixture, preventing re-burning. Also, shorter reaction times are expected at the higher mass flow rates. Biodiesel blends show lower CO emissions compared to diesel blends for all the cases and different equivalence ratios. The trend of lower CO emissions for biodiesel could be due to the oxygen content in biodiesel cooking oil which resulted in a more complete combustion than diesel oil [21, 22]. The variation in CO emission level according at different CO2 dilution rates is also shown Figure 4. For example, the reduction between B2 and B3 is ~36% for the equivalence ratio =1.7. The reason of this behaviour is due to the incomplete combustion of pockets of fuel combined with the short residence time so the CO formed in the combustion zone has less time to convert into CO_2 completely [16]. Thus, the high production of CO at B1, B2 and B3 is due to the incomplete combustion of pockets of fuels and further aggravated by the presence of CO in the fuels. Moreover, incomplete combustion is a factor that caused unburned hydrocarbons to have short residence time to react to form CO [16].

3.2. CH* chemiluminescence analyses

CH* chemiluminescence images were averaged (300 images) and analysed to get the planar flame structures via a Photron FASTCAM PFV Ver.3670 software and MATLAB R2016a. Figure 5 shows the planar flame structures of various swirling flames using diesel and biodiesel at equivalence ratio =1.6. CH* chemiluminescence excited from the flames can be used as a signal of heat release rate [24]. A Photron High-Speed Camera with a broadband long pass filter is used to reconstruct the region where soot is present. The band-pass filter for the CH* radicals is centered at 430 nm ±15 nm. Results show that luminescence from biodiesel blends flame is significantly different to diesel. Diesel flame show high CH* intensity peaks compared to the biodiesel flames especially for B1 due to its high sooting tendency. The high luminosity of the post-reaction zone region for B1, B2 and B3 flames is reflected in the high-intensity count as a result of soot radiation. The powerful luminosity is attributed to CH production as a result of the high content of aromatic rings in diesel. In contrast, biodiesel flames exhibit less CH chemiluminescence intensity within the combustor indicative of cleaner combustion with low level of soot formation. The presence of oxygen in the biodiesel augments the local combustion of hydrocarbons, whereas the lack of aromatic rings reduces the formation of soot and the sooty yellowish flame brush downstream.

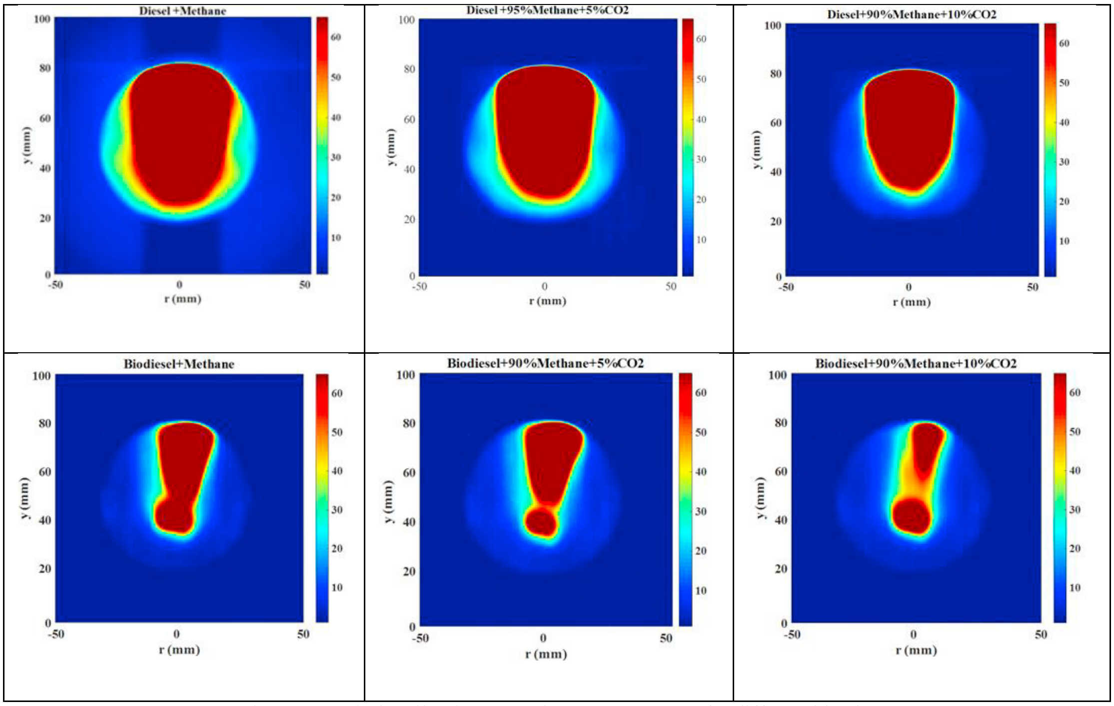

Figure 5. CH* chemiluminescence images at E.R. 1.6 for different blends.

Likewise, it has been reported that the soot generated from biodiesel is rapidly oxidised because of the initial combination of oxygen groups in the molecule [25]. On the other hand, results clearly show greater CH gain and soot for blends that did not contain CO2 (B1, B4), likely a consequence of poor mixing and high reactivity compared to other blends. Moreover, the high temperature of the CO2 in the CRZ will ensure a faster chemical reaction of the diluted reactants, thus allowing a stable regime with low emissions and lower temperatures. The low relative CH luminosity of the post-reaction zone region for blends with high CO2 concentration shows an enhanced, cleaner combustion. However, this phenomenon stops at higher CO2 concentrations, i.e. 20% when tested, which led to combustion only at the tip of the burner and troubles during ignition.

4. Conclusions

An experimental study on the combustion of CO2/CH4/biodiesel and CO2/CH4/diesel mixtures at atmospheric conditions were carried. The mixtures have been examined by using different levels of premixing with different equivalences ratios. Results showed that biodiesel blends reduced CO production during all tested conditions.

Moreover, these blends caused a reduction in emissions of nitrous oxides across all measurements. The introduction of CO_2 reduced the reaction rate and temperatures in the combustion zone, thus leading to a reduction in emissions of nitrous oxides as a consequence of a decrease in flame temperature. CH intensity profiles downstream the burner outlet for diesel blends and biodiesel blends were carried out as well. Diesel flames showed high CH intensity in the axial profile compared to biodiesel due to the high sooting tendency of the former. On the other hand, results clearly showed greater CH gain and soot for blends that did not contain CO2. In general CO2/CH4/biodiesel mixtures have produced the cleanest profiles with the best flame stability.

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