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Evaluating the Performance and Exhaust Emissions of a Micro Gas Turbine Engine Fueled by Kerosene and Olive Oil Methyl Ester Blends

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ABSTRACT

The search for renewable, affordable energy alternatives has gained momentum in light of dwindling fossil fuel reserves. Biofuels, particularly those derived from plant sources, present a viable solution to both the energy crisis and environmental degradation. This study focuses on the implementation of olive oil methyl ester (OME) biofuel in micro gas turbine engines. Biofuel blends, with volumetric OME concentrations ranging from 20% to 80% in standard kerosene, were prepared and tested on a GT 85-2-H micro gas turbine unit. The engine's performance and exhaust emissions were evaluated under two different operational parameters: constant speed and constant load. The use of an 80% OME biofuel blend resulted in an 8.7% reduction in overall efficiency and a 13.1% increase in specific fuel consumption (SFC) under an 80% load. However, it also led to a significant improvement in exhaust emissions, with reductions of 28.8%, 39%, and 33.8% recorded for carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x), respectively. Similarly, under a constant speed test at 20000 rpm, an 80% OME blend caused a 10.5% reduction in overall efficiency and a 13.6% increase in SFC. Nevertheless, the same blend improved the CO, HC, and NO_x emissions by 38%, 41.4%, and 36%, respectively. The findings confirm the potential of OME as a biofuel in micro gas turbine engines, underlining its effectiveness in reducing harmful emissions. This research emphasizes the feasibility of biofuels derived from olive oil in addressing future energy demands while mitigating environmental impact.

1. INTRODUCTION

The burgeoning demand for electricity in numerous developing nations often surpasses the generating capacities of their power plants, leading to frequent power outages. Such deficiencies are exacerbated by the weakness and obsolescence of transmission networks. One common strategy to mitigate the ramifications of these power losses is the implementation of rolling blackouts. During these periods of restricted power supply, backup generators provide an immediate source of electricity, supplementing the shortfall. These generators, with capacities spanning from several kilowatts to multiple megawatts, are prevalent across various sectors such as residential areas, hospitals, scientific laboratories, factories, telecommunications, and data centers. They are predominantly powered by diesel engines or heavy gas turbine units; however, micro gas turbines are increasingly being employed for smaller capacities.

Essentially, micro gas turbines are compact gas turbine units that have evolved from diesel engine turbochargers or aircraft auxiliary power units. Their generating capacities typically range between 1 kW and 500 kW. Capable of combusting an array of commercial fuels, including diesel, gasoline, kerosene, propane, natural gas, and liquefied petroleum gas (LPG), these units offer the potential to recuperate waste heat from high-temperature exhaust gas for utilization in water heating, space heating, drying processes, or absorption chillers. Given their ease of transportation and independence from the national grid, micro gas turbines constitute a rapidly expanding and promising source of distributed generation. They are particularly suited to serve as backup generators in residential, agricultural, and remote locations [1, 2].

The escalating consumption of fossil fuels to meet global energy needs, coupled with recurrent economic and political crises, leads to significant fluctuations in the prices of crude oil and petroleum products. Moreover, the indiscriminate use of fossil fuels contributes to global warming and atmospheric pollution. In light of these challenges, the promotion of renewable alternatives has become a top priority across the globe. Among the available renewable energy sources, biomass has emerged as a promising, affordable, and reliable option with broad industrial and economic applications. Biomass, either directly incinerated or processed into biofuels, is easily transported and has a high energy content. The majority of research in this area has focused on the use of biofuels in internal combustion engines, primarily diesel engines, due to the compatibility of biofuel properties with these engines. However, the versatility and simplicity of the fuel system in micro gas turbine units facilitate their use with renewable fuels such as E85 (85 percent ethanol and 15 percent hydrocarbon fuel by volume), biodiesel, and biogas [1].

Table 1 outlines the common biofuels alongside their properties that are pertinent to their use in power generators. The density and viscosity of biofuels, comparable to those of commonly used petroleum fuels, significantly influence atomization, smooth flow through fuel systems, and spray characteristics, all of which impact combustion efficiency. However, the lower heating values of biofuels restrict the energy released into the combustion space, thereby affecting engine performance and emissions. Nevertheless, biofuels are safe to transport and store due to their high flash point temperatures.

Biofuels utilized in diesel engines encompass cotton oil [3, 4], palm and coconut oils [5], waste cooking oils [6-9], rapeseed oil [10], canola oil [11], blends of rapeseed oil with canola and Jatropha oils [12], and olive and soya oils [13]. Challenges associated with the use of biodiesel, such as high viscosity, poor cold weather performance, and compatibility with diesel engine equipment, can be mitigated by blending the biodiesel with additives like Jet-A [14], kerosene [15], ethanol [16, 17], and nanoparticles [18, 19]. Spiritus and Pertalite [20], butanol and algae [21], and Pongamia [22] have been blended with spark ignition engines' fuel, resulting in improved emission of pollutants and enhanced specific fuel consumption (SFC).

A variety of alternative fuels have been considered for gas turbine units to enhance performance and reduce exhaust emissions, thanks to the flexibility of their fuel systems. Natural gas, heavy bunker oil, and diesel fuel have been tested in gas turbines, with the lowest carbon emissions being observed with natural gas [23]. The injection of ethanol into the compressor inlet air of a two-shaft micro gas turbine has been shown to improve power and brake-specific fuel consumption (BSFC) while lowering nitric oxide (NO_x) emissions in comparison to LPG as the primary fuel [24, 25]. Micro-gas turbines fueled with blends of straight rapeseed and sunflower oils with Jet-A1 have shown less sensitivity in NO_x and carbon monoxide (CO) emissions to fuel composition, while particle matter (PM) emissions are strongly dependent on the fuel type [26]. The performance and exhaust emissions of micro gas turbines powered by soybean oil, derived from energy crops, have also been investigated [27].

A notable investigation utilized blends of Ox-Tallow ethyl ester and kerosene in the Rover 1S/60 gas turbine engine. An increase in the ethyl ester content was found to considerably augment the SFC whilst simultaneously reducing CO and unburned hydrocarbons (HC) emissions. Interestingly, NO_x emissions were observed to decrease with a higher proportion of ethyl ester, attributable to lower combustion temperatures [28]. Distinct fuel blends derived from rapeseed and canola-sunflower oil, enhanced with ethanol and Pentanol, demonstrated an increase in static thrust and an improvement in thrust-specific fuel consumption. When compared with neat Jet-A fuel, the emissions of NO_x, CO, and HC were discernibly reduced [29]. The potential of biojet fuel produced from hydro-treated coconut oil as an alternative aviation fuel suitable for tropical regions was also examined. In a blend with Jet A-1, the fuel was used to operate a Rover 1S/60 gas turbine engine. Performance parameters and emissions of CO, HC, and NO_x were comparable to those of Jet A-1, with a marked decrease in smoke opacity [30]. Further studies involved the turbofan DGEN380 engine, tested with blends of Jet-A and either alcohol or hydrolyzed esters and fatty acids derived from used cooking oil. An increase in the bio-components' proportion resulted in a significant rise in CO emissions with a marginal rise in NO_x and HC [31]. In addition, the performance and emission characteristics of a blend of Jet A-1 and 20% Soap-derived biokerosene (SBK) were assessed in a Rover 1S/60 gas turbine engine at variable engine brake power. The performance was nearly identical for both pure Jet A-1 and the blended fuel. However, slight increases in CO, HC, and NO_x emissions were documented as the proportion of SBK increased [32]. An experimental study on a small jet engine revealed that a microalgae blend in Jet-A, ranging from 20% to 100%, enhanced thrust and efficiency. Furthermore, carbon dioxide (CO_2), CO, and NO_x emissions were improved at lower proportions [33]. Remarkable efficiency improvement was achieved with a mixture of 90% Jet-A, 10% glycerin, and 50 ppm TiO_2, which was tested on a micro gas turbine. This blend resulted in lower fuel consumption compared to neat Jet-A fuel and improved efficiency by 22% [34]. A micro-gas turbine fueled by biofuel containing either 20% palm oil, 15% coconut oil, or 30% Jatropha oil exhibited a reduction in maximum temperature compared to neat diesel fuel. Palm oil resulted in the least reduction (3.4%), whereas Jatropha oil led to the greatest reduction (11.4%) [35]. In another study, a micro gas turbine powered by a blend of 15% waste cooking oil in kerosene displayed similar SFC to that of a neat kerosene run. However, a high blend of 90% significantly reduced exhaust emissions at the cost of the resultant thrust [36]. Biodiesel fuel sourced from animal fats was used in a micro gas turbine, with plasma combustion technology being employed to characterize performance and emissions. Biofuels gave rise to fewer NO_x, CO, and sulfur emissions than neat diesel. Thermal efficiency and thrust were considerably amplified at higher unit loads [37]. The concept of an integrated gasification plant comprising a micro gas turbine was proposed to simultaneously generate electricity and dry olive pomace, thus reducing handling and disposal costs in Spain's olive oil industry. At optimal operation, the electrical efficiency was 18.8%, and due to pomace drying, the overall efficiency increased to 51% [38]. Lastly, hydrogen is being increasingly viewed as a compelling alternative to fossil fuels in gas turbines, owing to its zero-emission characteristics and high energy content. The performance of a gas turbine unit's components under varying conditions, using hydrogen as a fuel, correlates with its optimal operation [39].

The burgeoning interest in biofuels for power generation devices holds significant potential for invigorating the agricultural sector, particularly among farmers and food producers. This shift could foster the development of local communities, increase resource allocation, and stimulate the rehabilitation of outdated machinery to create biofuel-operated backup generators. The production and marketing of biomass also contribute to job security, rural lifestyle enhancement, and urban migration reduction, simultaneously alleviating socio-economic pressures on civil societies. By augmenting the production of biofuels from prevalent regional crops, we may anticipate a reduction in production costs, rendering them competitive with depleting petroleum fuels, the prices of which are subject to volatility in response to crises and consumption fluctuations. Local biofuel production could potentially mitigate dependency on imports, thereby securing a low-cost supply chain for fueling backup generators.

Over the past two decades, Iraq's agricultural sector has experienced a decline in both cultivated areas and yield, primarily due to the influx of competitively priced imported crops saturating the local food market. This has resulted in significant waste of agricultural products, exacerbated by the region's hot climate and the high operational costs of cold storages, which rely heavily on backup generators during power outages. Non-essential fruits, such as olives, have been particularly affected due to their high prices compared to other foodstuffs, making them less affordable for lower-income households. This trend discourages farmers from cultivating olives, leading to recurrent financial losses each season. Therefore, immediate measures are necessary to incentivize farmers to maintain their cultivation areas and offset their financial losses. Providing marketing solutions and investing surplus quantities of olives for raw fuel production represents a viable strategy. This approach could make fuel more accessible and desirable for owners of low-capacity generators, fulfilling local energy demands.

Table 1. Physical properties of common biofuels

Fuel	Density kg/m³	Kinematic Viscosity mm²/s	Heating Value kJ/kg	Flash Point °C
Cotton seed [3]	882	6.8	39540	173
Palm [5]	827	4.2	42500	140
Waste cooking oil [8]	882	4.3	38600	179
Canola [11]	880	4.2	39490	182
Soybean [13]	872	5.5	39300	96
Tamarind [18]	836	3.9	41400	77
Algae [21]	886	4.5	-	115
Ethanol [29]	795	1.8	26700	35
Rapeseed [29]	912	5.9	39470	246
Sunflower [29]	883	5.2	37100	140
Coconut [30]	756	3.8	43900	36
Animal fat [37]	873	4.3	-	97
Pongamia [40]	917	5.5	-	110
Jatropha [41]	900	4.9	39808	138
Waste olive oil [42]	858	4.5	40488	110

The challenge of securing jet fuel for micro gas turbine generators places financial burdens on homeowners, farmers, and small investors, leading to recurrent power outages and impacting economic productivity. Transitioning to a fuel commonly used for everyday activities, such as cooking and heating, represents a pragmatic solution due to its availability and lower cost. Commercial kerosene fuel emerges as an appropriate alternative for this consumer segment, potentially rationalizing their expenses and ensuring a continuous electricity supply during rolling blackouts.

Despite numerous studies on biofuels, there is a notable lack of research investigating olive oil-derived biofuel as a potential fuel source for power generators, especially micro gas turbines. This gap in knowledge motivates further exploration into the suitability of olive oil as a fuel source, whether in liquid biofuel form or as biomass from olive pomace. The present study experimentally investigates the effects of olive oil biofuel on the GT 85-2-H two-shaft micro gas turbine's performance and pollutant emissions. Success in this area could encourage small-scale investors and farmers in Iraq to expand olive cultivation to meet energy demands during frequent power outages. Additionally, this study could stimulate local beneficiaries to establish a manufacturing plan for micro gas turbine generators operating on this locally produced biofuel, which could improve their financial status.

The study conducts tests at a constant power turbine speed of 20000 rpm across an engine load range of 40% to 90%, and at a constant power turbine load of 80% over a power turbine speed range of 15000 to 27000 rpm. Biofuels are prepared by combining olive oil methyl ester at concentrations of 20%, 40%, 60%, and 80% with commercial kerosene. The study assesses the overall efficiency, specific fuel consumption, and CO, HC, and NO_x emissions of the GT 85-2-H micro gas turbine engine. This study provides a comprehensive analysis of the impacts of olive oil methyl ester utilization on engine performance and emission characteristics.

2. EXPERIMENTAL METHODS

2.1 Materials

All materials involved in this study were purchased from the local Iraqi market. The base kerosene fuel was sourced from local petrol stations. The 96.9% pure ethanol (C_2H_5OH), 95% pure methanol (CH_3OH), and, sodium hydroxide (NaOH) were sourced from local private dealers in chemical and medical products. The specifications and standard conformity of all materials involved in the study were issued by an authorized institution.

2.2 Biofuel preparation

Vegetable oils are highly viscous materials compared to traditional fossil fuels, which makes them less suitable for use in internal combustion engines. Transesterification is a process in which vegetable oil is reacted with alcohol in the presence of a base catalyst under atmospheric pressure and about 65°C [8]. In this study, virgin olive oil is used to produce the methyl ester by reacting with methanol using NaOH as a catalyst.

Methoxide is prepared by dissolving 5 grams of NaOH in 200 mL of methanol. The olive oil is kept in a 2000 mL reactor while being heated and continuously stirred before methoxide is added and stirred for 30 minutes to ensure reactivity and process acceleration. The mixture is left for 24 hours to ensure complete phase separation in which methyl ester forms the upper layer while glycerol and excess methanol take the lower layers. Water washing of the resultant methyl ester to remove methanol and other impurities is repeated until reach the desired purity of the biofuel ester. The water is then extracted by heating the biofuel beyond 100°C and the purified olive oil methyl ester is eventually ready to be blended with neat kerosene.

The biofuel is composed by blending neat kerosene with olive oil methyl ester in a specified blending ratio. Thus, the tested biofuels are prepared with four concentrations of methyl ester in neat kerosene. The study uses base kerosene as a reference and is designated as K100. The biofuels are designated by their percentage of methyl ester in neat kerosene. As an example, B20 stands for a blend comprising 20 percent olive oil methyl ester and 80 percent neat kerosene on a volume basis. The blending ratios adopted in this study include 20%, 40%, 60%, and 80% olive oil methyl ester. The properties of neat kerosene and biofuels are listed in Table 2.

Table 2. Characterization of test fuels

Fuel	Density kg/m³	Kinematic Viscosity mm²/s (40°C)	Lower Heating Value kJ/kg	Flash Point °C
K100	801	2.7	43100	38
B20	867	6.6	42030	43
B40	874	8.2	41503	51
B60	879	9.7	40542	55
B80	886	10.6	39987	59

2.3 Test engine

Two-shaft Gilkes-Rollab GT-85-2-H micro gas turbine engine was employed for testing various blends of olive oil-derived biofuel and evaluating their effect on the engine's performance and exhaust emissions. The test engine specifications are listed in Table 3, along with Figure 1 showing the rig setup. The gas generator comprises a back-to-back radial compressor and turbine rotating at speeds up to 90,000 rpm on a common shaft. On the other hand, the radial power turbine is installed on a separate shaft that is energized by the exhaust gases leaving the gas generator and rotates at speeds up to 35,000 rpm. The output of the power turbine is measured by an eddy current dynamometer mounted on the power turbine shaft using load cells that digitally display the produced torque. The load exerted on the power turbine is adjusted via a variable resistance controlling the exciting current applied to the dynamometer. The working fluid pressure and temperature at vital stations are measured using temperature and pressure sensors and converted by an analog system into signals sent to the computer for recording and analysis. The rotational speeds of gas generators and power turbines are measured using opto-electronic tachometers. The air flow rate is measured using an orifice plate according to the pressure differential of a water manometer, while the fuel consumption is metered using a calibrated scale rotameter. The AIRREX HG-540 gas analyzer was employed to measure pollutant emissions using an extraction probe inserted into the engine exhaust stack. The pollutants detected are CO, HC, and NO_x.

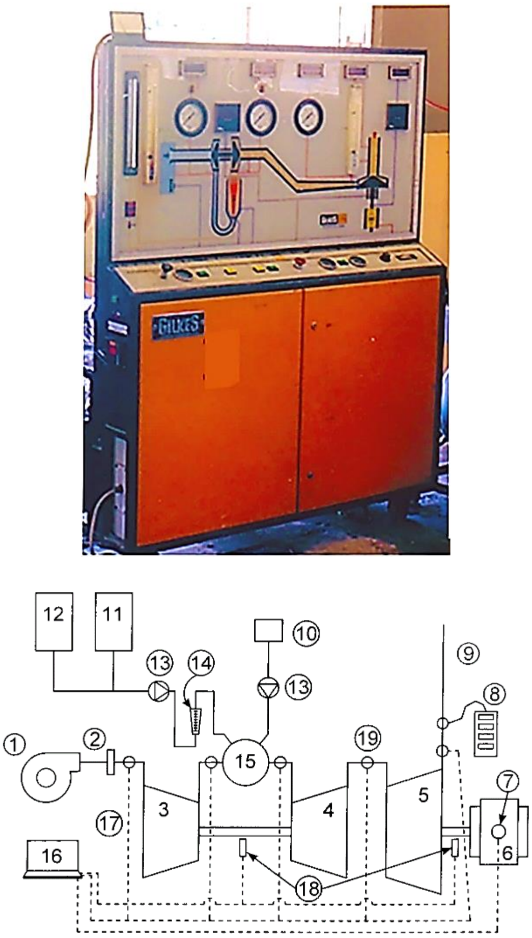
Table 3. Specifications of test engine [43]

Primary Fuel	Kerosene
Starting Fuel	Ethanol
Overall Pressure ratio	2/1 nominal
Gas Generator Speed	90000 rpm max
Power Turbine Speed	35000 rpm max
Power Output	5 kW nominal
Firing Temperature	700-750°C max
Oil Cooler Water Flow	18 L /min
Electrical Supply	220-240 V

The simple structure of the GT-85-2-H engine makes it a suitable candidate for the purpose of the study. The engine is basically a turbocharger of a diesel engine connected to a combustion chamber and an electric generator, which are components that can be easily sourced from the local market. For this reason, farmers, homeowners, and small investors have the ability to manufacture and employ the engine to burn olive oil biofuels. In addition, the simple design of the combustion chamber makes it more flexible to burn different types of liquid fuels including olive oil biofuels. Therefore, these characteristics of the micro gas turbine GT-85-2-H encourage us to choose it for this study.

2.4 Test procedure

The testing procedure starts by running the micro gas turbine unit on neat kerosene fuel at the desired operating condition and providing the benchmark data. Afterward, the unit is switched to run on the prescribed percentage of biofuel at the same operating condition. At startup, four fans are run to deliver air flow to rotate the compressor and produce the required pressure ratio. In addition, these fans are used to supply sufficient airflow into the combustion chamber to achieve the combustion of the injected fuel. The combustion commences by injecting ethanol into the combustion chamber and igniting it with a spark plug to produce the pilot flame, overcoming any startup difficulties. Thereafter, the main fuel is introduced into the combustion chamber to be ignited by the pilot flame. When a sustainable flame is secured, the ethanol is cut off and the unit continues to run on the target fuel to be tested.



1	Starting fans	11	Kerosene fuel tank
2	Orifice plate	12	Blended fuel tank
3	Centrifugal compressor	13	Fuel gear pump
4	Gas generator turbine	14	Fuel rotameter
5	Free power turbine	15	Combustion chamber
6	Dynamometer	16	Computer
7	Load cell	17	Data transfer cables
8	Gas analyzer	18	Tachometers
9	Exhaust stack	19	Pressure/temperature sensors
10	Alcohol fuel tank		

Figure 1. Test rig setup

Two test strategies based on the variable load mode or the variable speed mode of the power turbine are adopted. The power turbine load and speed were correspondingly controlled by adjusting the value of the dynamometer resistance exerted on the power turbine and the fuel injection rate. The constant speed tests are conducted at a load range between 40 and 90% of the power turbine's full load while maintaining a power turbine speed of 20000 rpm. On the other hand, constant power turbine loading tests are conducted at a range of power turbine speeds between 15000 and 27000 rpm while keeping the power turbine at 80% of full load.

The reliability of the data acquired requires that each test to be conducted under steady engine run. Therefore, the measurements were recorded after all temperature and pressure readings were stabilized at the vital stations on the working fluid path, which takes between 10 to 15 minutes. The values of the measured variables were averaged over a 30 second period to maintain the standard deviation around the mean value [31]. Data reliability was ensured by repeating each test for at least four times to approve reading for record and analysis.

2.5 Uncertainty

There will always be differences between the true values and the measured values, and these are considered errors. Errors in measurements are unavoidable, and they arise due to the inconstancy and inherent degradation of selected instrumentation. Error analysis is obligatory to prove the reliability of the experimentally acquired results. The current error analysis follows the approach described by Coleman and Steel [44]. The uncertainties associated with the measurements are listed in Table 4.

Table 4. Accuracy of instrumentation

Instrument	Accuracy	Uncertainty
Torque meter	± 0.08 N m	± 0.2%
Thermometer	± 1°C	± 0.15%
Tachometer	± 10 rpm	± 1%
Rotameter	± 0.1 mL	± 1%
Manometer	± 1 mm	± 1%
Gas Analyser		
NO_x	± 5 ppm	± 0.2%
CO	± 10 ppm	± 0.2%
HC	± 5 ppm	± 0.2%

The value of a certain parameter depends on several independent variables:

$$R = R\left(X_1, X_2, X_3, \ldots\ldots X_n\right) \tag{1}$$

Hence, the uncertainty in *R* will be calculated as:

$$W_R = \sqrt{\sum_{i=1}^{i=n}\left(\frac{\partial R}{\partial X_i}\times W_{Xi}\right)^2} \tag{2}$$

For example, if considering the *SFC* which is given by:

$$SFC = \frac{\dot{m}_F}{P_B} \tag{3}$$

According to Eq. (2), then:

$$W_{SFC} = \sqrt{\left(\frac{\partial SFC}{\partial \dot{m}_F}\times W_{\dot{m}_F}\right)^2 + \left(\frac{\partial SFC}{\partial P_B}\times W_{P_B}\right)^2} \tag{4}$$

The maximum error detected in SFC is ±2.9% over the entire experimental data. In that context, the maximum deviations all over the system never exceed ±4.1% which is acceptable for practical considerations.

3. RESULTS AND DISCUSSION

Tests were performed to examine the effect of blending olive oil methyl ester with neat kerosene fuel at different concentrations on the peformance and exhaust emissions of a two-shaft Gilkes-Rollab GT-85-2-H micro gas turbine under two testing strategies. The first strategy is a constant power turbine speed of 20000 rpm at loads of 40%, 50%, 65%, 80% and 90% of full unit load. The second strategy is a constant power turbine load of 80% at speeds of 15000, 18000, 21000, 24000 and 27000 rpm.

The emission values presented in this section comply with the gas turbine regulations. Therefore, all emissions were expressed on a dry basis and normalized to 15% O_2 in exhaust gas [45, 46].

3.1 Effect of power turbine speed

Figure 2 depicts the change in overall efficiency with power turbine speed at various biofuels ratios. More viscous biofuels make the atomization poorer resulting in less efficient combustion compared to neat kerosene run [1, 3, 4]. In addition, the lower heating value of biofuel needs more fuel to be burned at the same turbine speed. Consequently, if the percentage of methyl ester in biofuel increases, a further reduction in overall efficiency can be observed at all turbine speeds, which is comply with the findings of Singh et al. [4], Al-Saraf and Al-Jumaily [24], and Silva et al. [28]. Results indicate that B20 has the highest efficiency among all blends and it gives an average 3.1% reduction with respect to K100. However, the drop in efficiency is about 8.7% averaged over the speed range for B80 and is the lowest of all biofuels.

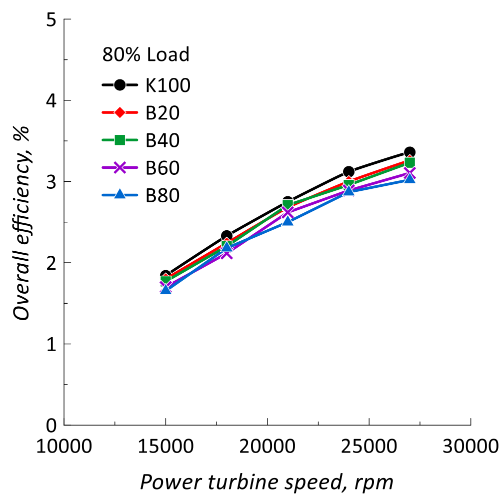


Figure 2. Overall efficiency at different turbine speeds

Increasing the percentage of methyl ester in biofuel causes SFC to worsen owing to the additional fuel consumption needed to maintain the same turbine speed, as shown in Figure 3. The increase in SFC for B20 is 6.8% in comparison to K100 consumption. However, with B40, only an 8.1% increase in SFC was obtained compared to K100 run. B60 and B80 show 12.4% and 13.1% higher consumption, respectively, than that of K100. These trends are agreed with results presented by Singh et al. [4], Bayindir et al. [11], Al-Saraf and Al-Jumaily 24], even though, no perceptible differences in performance between conventional fuel and biofuels were reported by Przysowa et al. [31].

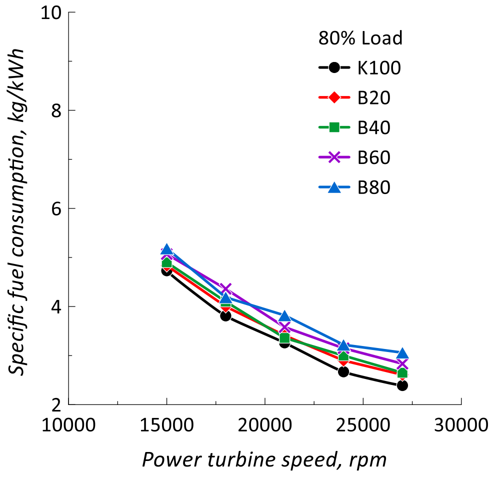


Figure 3. SFC at different power turbine speeds

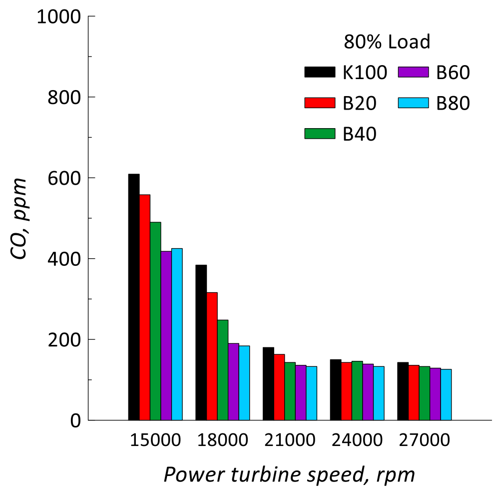


Figure 4. CO emission at different power turbine speeds

Incomplete combustion of the injected fuel is indicated by the emission of CO in exhaust gas. Increasing fuel consumption as the turbine speed increases brings CO to a point where its level is the lowest with proper fuel/air ratio to approach complete combustion. This tendency is clearly depicted in Figure 4 for all types of fuel burned over the turbine speed range. Nevertheless, a higher percentage of methyl ester in biofuel means additional oxygen is released into the reaction space which achieves a better reaction rate towards the completion of combustion and a further reduction in CO emissions. In that context, the improvement in CO emissions is about 9.6%, 18.8%, 27.4% and 28.8% for B20, B40, B60 and B80 respectively compared to neat kerosene K100 levels as averaged over the entire speed range. These outcomes are concurred in the studies of Singh et al. [4], Manigandan et al. [29], Reksowardojo et al. [32], and Alrashidi et al. [37], while Al-Saraf and Al-Jumaily [25] reported an increase in CO emission with higher ethanol percentage. This can be attributed to the premixing of ethanol with air before the combustion chamber, as well as the fact that the main fuel was gaseous LPG. Further, there is an inconsistency with the results of Cavarzera et al. [27] who used straight blending of untreated vegetable oils with diesel fuel.

Figure 5 indicates the emission of HC with increasing turbine speed for various biofuels. Same causes of CO emissions are applicable here for the HC emissions. Amounts of HC release depend on the fuel characteristics and oxygen availability in the reaction space. The combination of oxygen atoms in air and biofuel improves the combustion efficiency and reduces HC in exhaust gas [31]. Figure 5 depicts the high discrepancy between emission levels at low speeds that is gradually reduced when levels are getting close in high speed range. This closeness is attributed to less residence time available for the combustible mixture at high speeds. Therefore, average reduction in HC levels for B20, B40, B60, and B80 is about 14.5%, 28%, 35.4% and 39% respectively in comparison to the corresponding K100 emission levels. Although these results comply with those studies of Sutheerasak et al. [16] and Jagtap et al. [17], they are the contrary of the studies of Pullagura et al. [18], Al-Saraf and Al-Jumaily [25] as both included ethanol and gaseous fuel in biofuel composition which rise the carbon and hydrogen molecules in combustion chamber.

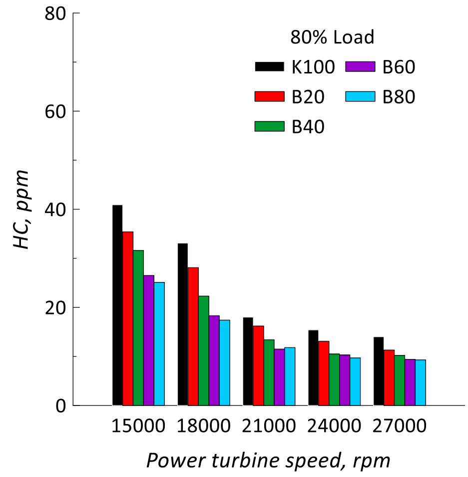


Figure 5. HC emission at different power turbine speeds

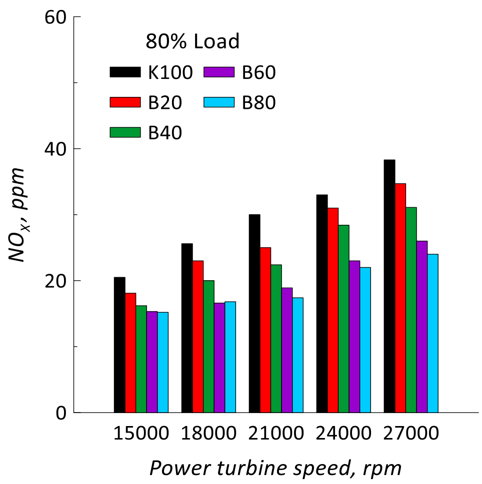


Figure 6. NO_x emission at different power turbine speeds

Figure 6 demonstrates the NO_x emissions with increasing power turbine speed for the various biofuels tested. NO_x emission refers to the higher temperature in combustion chamber due to the higher energy release, in addition to oxygen abundance in the reaction space which promotes the formation of NO_x. Higher fuel consumption in the high speed range results in higher NO_x emissions for all fuels involved. Yet, less NO_x is emitted when the percentage of methyl ester in biofuel is increased because of the lower heating value that reduces the combustion temperature [2]. The reduction in NO_x

emission is 10.9%, 20.4%, 31.7% and 33.8% for B20, B40, B60, and B80 respectively compared to the conventional NO_x emission for K100. In general, this trend agrees well with the results reported by Cavarzera et al. [27], Manigandan et al. [29], Reksowardojo et al. [32], and Alrashidi et al. [37].

3.2 Effect of power turbine loading

The higher loading of a micro gas turbine requires more fuel to be burned and this results in higher combustion temperatures. This effect will improve the utilization of air-fuel mixing in the combustion chamber and improve overall unit performance at higher loads [3, 4, 24].

The variation of overall efficiency with power turbine loading is shown in Figure 7 where increasing olive oil methyl ester in biofuel lowers the efficiency owing to the lower heating value of these blends. Same conclusions were generally given by Al-Saraf and Al-Jumaily [24], Silva et al. [28], and Reksowardojo et al. [32]. For B20, the percentage reduction in efficiency is 2.4% compared to K100 run. However, for the higher biofuel B80 the reduction reaches 10.5% in comparison to the conventional K100 run.

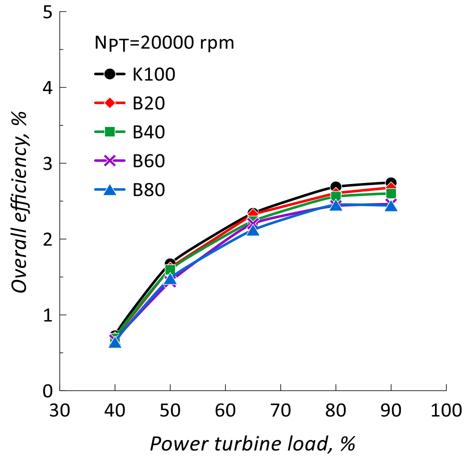


Figure 7. Overall efficiency at different power turbine loads

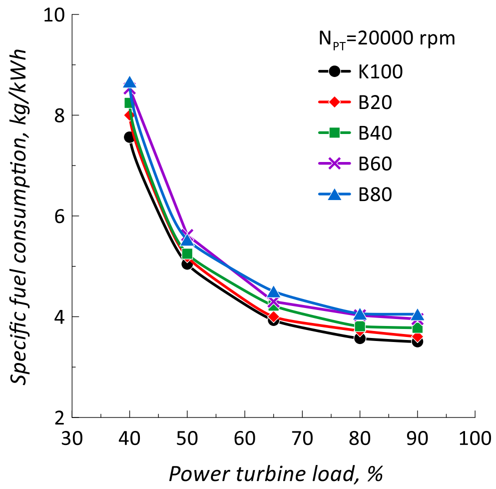


Figure 8. SFC at different power turbine loads

Evident differences in SFC are shown in Figure 8 among the fuels tested especially along the lower loading range, where higher fuel consumption corresponds to lower power output. Nevertheless, these differences are decreased at higher loads due to better energy utilization and higher outputs. Still much fuel has to be burned with increasing methyl ester concentration in biofuel due to the lower heating values [4, 11, 24]. The average increase of SFC compared to kerosene run is about 3.4% and 7% for B20 and B40 respectively. Nevertheless, the increase reaches 11.8 % and 13.6% for B60 and B80, respectively.

In general, increasing power turbine loading leads to mitigate CO emission as mixture strength reaches a value appropriate to approach complete combustion. This effect is in accompanying of higher burning temperatures which motivate reaction rates and improve combustion efficiency, as shown in Figure 9. The presence of oxygen within biofuels further improves the reaction rates and reduces the CO emissions which agrees with the studies of Reksowardojo et al. [32] and Alrashidi et al. [37]. The recorded CO levels for B20, B40, B60, and B80 were 12.4%, 28%, 36% and 38% less than the neat kerosene K100 emission, respectively. However, there is a contradiction with the results presented by Cavarzera et al. [27], as a result of blending straight vegetable oils into pure diesel fuel without pretreatment.

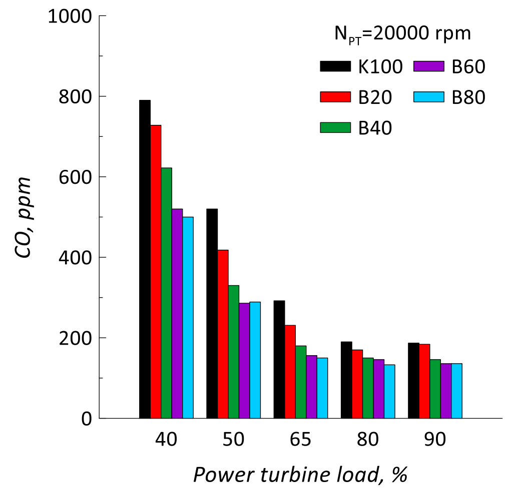


Figure 9. CO emission at different power turbine loads

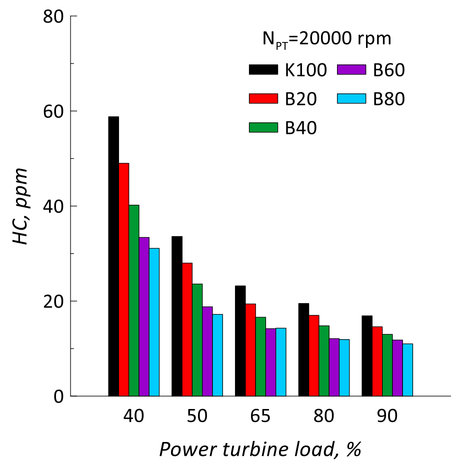


Figure 10. HC emission at different power turbine loads

Figure 10 elucidates the reduction in HC emission with increasing power turbine loading due to the same reasons explored with CO previously. However, it is clear that HC rapidly decreased with raising the load as a result of more favorable oxidation of hydrocarbon components in fuel. Yet, at higher loads the emission levels are less steep as hydrocarbon components are depleted due to better reaction rates. Increasing methyl ester percentage in biofuel makes HC emissions even better. In the range of loads considered, the decrease in HC emission is about 15.5%, 28%, 36% and 41.4% for B20, B40, B60, and B80 respectively with respect to the K100 levels. These results are consistent with those provided by Sutheerasak et al. [16], Jagtap et al. [17], Cavarzera et al. [27], and Reksowardojo et al. [32] from a qualitative perspective.

Inherited high temperatures with increased loading stimulate the formation of NO_x, as exhibited in Figure 11. However, burning temperature is related to the energy released into combustion chamber which depends on the fuel heating value as stated by Cavarzera et al. [27], Manigandan et al. [29], and Reksowardojo et al. [32]. Thus, increasing percentage of methyl ester in biofuel reduces burning temperatures, as well as, NO_x emissions in exhaust gas [2]. In that context, NO_x emissions are reduced by 8.5%, 16%, 23.3%, and 36% with respect to K100 levels for B20, B40, B60, and B80 respectively.

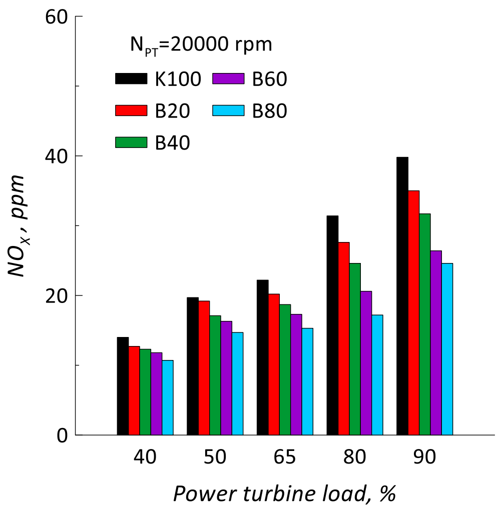


Figure 11. NO_x emission at different power turbine loads

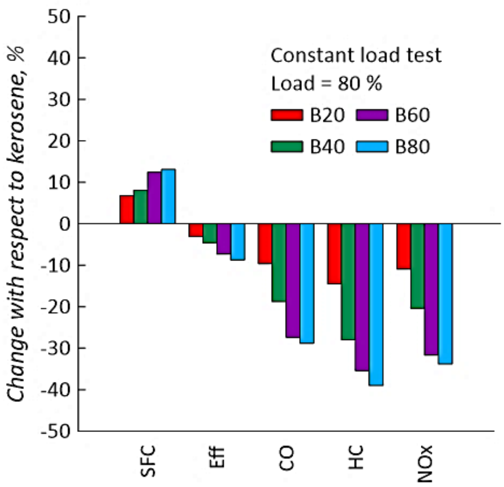


Figure 12. Percentage change in performance and emissions compared to base kerosene, at constant load

To present a comprehensive realization of the extent of improvement with using olive oil derived biofuel, the percentage changes in performance and emissions characteristics are compared explicitly relative to the reference kerosene in Figures 12 and 13. The comparisons are based on average percentage changes over the whole engine load and speed ranges. The performance degradation is only one tenth, while emissions are reduced by one third compared to kerosene levels. The improvement in emissions clearly outweighed the deterioration in performance parameters, with emissions suppressed by nearly two-thirds compared to the decline in performance. This superiority certainly establishes the replacement of fossil fuels with olive oil biofuel due to its positive impact on environmental aspects.

Previous results demonstrated the feasibility of running gas turbine engines on biofuels derived from olive oil over a wide range of engine loads and rotational speeds. It has been shown that the small regress in performance is fairly compensated by the significant improvement in pollutants emissions. Employing micro gas turbine generators for sectors with low power demands has proven to be affordable and reliable, which encourages farmers, homeowners, and small investors to participate in biofuel investment to improve their lifestyle and achieve economic growth for their communities.

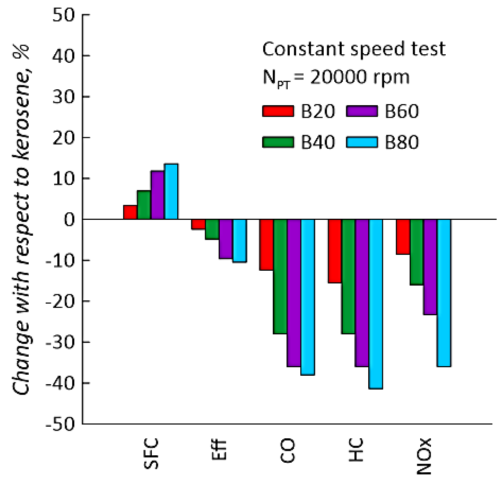


Figure 13. Percentage change in performance and emissions compared to base kerosene, at constant speed

4. RECOMMENDATIONS FOR FUTURE WORKS

As the previous literature revealed, it is clear that there is a scarcity of testing olive oil either in its liquid form or in solid pomace form to fuel various power generators, and to the best of the authors' knowledge; olive oil biofuel has not been tested as a fuel in large or micro gas turbine engines. In addition, since the current study is a bounded analysis to GT 85-2-H micro gas turbine under its pertinent design, comprehensive studies on other micro gas turbines or even larger units employing alternative biofuels derived from olive oil methyl esters are highly recommended.

An exergy analysis with respect to second law efficiency, irreversibility etc., will take the assessment farther deeper into optimizing the operating limits of individual engine components under the olive oil methyl esters specification.

Despite the environmental consequences of using olive oil methyl esters, a cost analysis is recommended to assess the economic feasibility of using this biofuel to balance the additional fuel expenditure with the cost savings of pollution treatment.

Acquired emission data should be invested in developing an extensive prediction model of engine pollutant emissivity to correlate biofuel properties with the performance parameters in an elementary framework.

5. CONCLUSIONS

The GT 85-2-H two-shaft micro gas turbine was tested to evaluate the effects of using biofuels derived from olive oil methyl ester on performance and emission characteristics. The experimental investigation covered a range of rotational speeds from 15000 to 27000 rpm, as well as a range of loads from 40% to 90% of full engine load. The tested biofuels were prepared with methyl ester concentrations ranging from 20% to 80% in commercial kerosene to realize the risks associated with using the tested biofuels on performance and fuel consumption.

The study reveals a significant mitigation in the environmental impacts of burning fossil kerosene when it is replaced by a biofuel derived from olive oil, which is expressed through the apparent reduction in pollutant emissions. Although the results indicate a slight decline in engine performance, this decline is practically offset by the improvement in exhaust emissions.

The important results of the study can be summarized as follows:

- The reduction in overall efficiency reaches 8.7% with 80% methyl ester in biofuel over the turbine speed range. Yet, the reduction is up to 10.5% at variable turbine loading with 80 % methyl ester in biofuel.
- The rise in SFC with 80% methyl ester in biofuel is 13.1% in variable speed runs, while the rise becomes 13.6 % with this biofuel concentration in variable turbine loading runs.
- An improvement in CO emission of 28.8% is achieved with an 80% biofuel in a variable-speed run. However, a 38% improvement is achieved for this biofuel with the variable load run.
- HC emission is improved by 39% in a variable speed run, while the improvement reaches 41.4% as averaged in a variable loading run, both when burning an 80% biofuel.
- The decrease in NO_x emissions is 33.8% as an 80% methyl ester biofuel is burned in a variable-speed run. In a variable loading run, the decrease reaches 36% due to the lower combustion temperature of the 80% biofuel.
- In general, olive oil derived biofuels provide a clear suppression in exhaust emissions by over one third while performance only deteriorates by one tenth, compared to K100 run.

The findings of this study are agreed well with those presented by Al-Saraf and Al-Jumaily [24], Silva et al. [28], and Reksowardojo et al. [32] regarding engine performance, although Przysowa et al. [31] reported no perceptible differences. The emissions of CO and HC are complied with trends provided by Manigandan et al. [29], Reksowardojo et al. [32], and Alrashidi et al. [37] but in evident contrast to those given by Al-Saraf and Al-Jumaily [25] and Cavarzera et al. [27]. NO_x emissions however, are in compliance with those demonstrated by Cavarzera et al. [27], Manigandan et al. [29], Reksowardojo et al. [32], and Alrashidi et al. [37].

The foregoing conclusions indicate the supreme characteristics of gas turbine performance and exhaust emissions with olive oil methyl esters. The decline in overall efficiency and specific fuel consumption is marginal for practical consideration. However, the eminent reduction in exhaust emissions when using olive oil biofuels offsets the decline in performance criteria of gas turbine generators. This study justifies the shift towards alternative fuels to eliminate dependence on fossil fuels and mitigate the devastating effects of pollution on the environment and living organisms.

REFERENCES

[1] Aslanidou, I., Rahman, M., Zaccaria, V., Kyprianidis, K. (2021). Micro gas turbines in the future smart energy system: Fleet monitoring, diagnostics, and system level requirements. Frontiers in Mechanical Engineering, 7: 676853. https://doi.org/10.3389/fmech.2021.676853

[2] Agelidou, E., Seliger-Ost, H., Henke, M., Dreißigacker, V., Krummrein, T., Kutne, P. (2022). The heat-storing micro gas turbine - process analysis and experimental investigation of effects on combustion. Energies, 15(17): 6289. https://doi.org/10.3390/en15176289

[3] Bayindir, H. (2007). Performance evaluation of a diesel engine fueled with cotton oil kerosene blends. Journal of New World Science Academy, 2(1): 30-38.

[4] Singh, S., Nayyar, A., Goyal, R., Saini, M. (2019). Experimentally optimization of a variable compression ratio engine performance using different blends of cotton seed with diesel fuel at different compression ratio. International Journal of Mechanical Engineering and Robotics Research, 8(1): 121-128. http://doi.org/10.18178/ijmerr.8.1.121-128

[5] KalaM, M., Masjuki, H., Jayed, M., Liaquat, A. (2011). Emission and performance characteristics of an indirect ignition diesel engine fuelled with waste cooking oil. Energy, 36(1): 397-402. https://doi.org/10.1016/j.energy.2010.10.026

[6] Gad, M., El-Baz, F., El-Kinawy, O. (2015). Performance of diesel engines burning used cooking oil biodiesel. International Journal of Mechanical & Mechatronics Engineering, 15(3): 74-80.

[7] Jaharudin, N., Ramlan, A., Hamzah, M., Abdullah, A. Mamat, R. (2015). Study on particulate matter of diesel engine using waste cooking oil. Applied Mechanics and Materials, 773-774: 420-424. http://doi.org/10.4028/www.scientific.net/AMM.773-774.420

[8] Abed, K., El-Morsi, A., Sayed, M., El-Shaib, A., Gad, M. (2018). Effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine. Egyptian Journal of Petroleum, 27(4): 985-989. https://doi.org/10.1016/j.ejpe.2018.02.008

[9] Mandal, A., Choc, H. (2021). Waste cooking oil as fuel in ci engine - a review. International Journal of Mechanical Engineering and Robotics Research, 10(9): 485-492. https://doi.org/10.18178/ijmerr.10.9.485-492

[10] Labecki, L., Ganippa, L. (2012). Effects of injection parameters and EGR on combustion and emission characteristics of rapeseed oil and its blends in diesel engines. Fuel, 98: 15-28. http://doi.org./10.1016/j.fuel.2012.03.029

[11] Bayindir, H., Isik, M., Aydin, H. (2017). Evaluation of combustion, performance and emission indicators of canola oil-kerosene blends in a power generator diesel engine. Applied Thermal Engineering, 114: 234-244. https://doi.org/10.1016/j.applthermaleng.2016.11.184

[12] Delalibera, H., Johann, A., De Figueiredo, P., De Toledo,

A., Neto, P., Ralisch, R. (2017). Performance of diesel engine fuelled with four vegetable oils, preheated and at engine working temperature. Journal of Brazilian Association of Agricultural Engineering, 37(2): 302-314. https://doi.org/10.1590/1809-4430-Eng.Agric.v37n2p302-314/2017
[13] Emetere, M., Jack-Quincy, S., Adejumo, A., Dauda, O., Osunlola, I., Adelekan, D., Adeyemi, O. (2018). Empirical analysis of biodiesel effect on the automobile properties of diesel engine: A case study of olive and soya biomass. Energy Science & Engineering, 6(6): 693-705. https://doi.org/10.1002/ese3.244
[14] Chiatti, G., Chiavola, O., Palmieri, F. (2019). Impact on combustion and emissions of jet fuel as additive in diesel engine fuelled with blends of petrol diesel, renewable diesel and waste cooking oil biodiesel. Energies, 12(13): 2488. http://doi./10.3390/en12132488
[15] Gad, M., Islami, M. (2021). Effect of waste cooking oil biodiesel blending with gasoline and kerosene on diesel engine performance, emissions and combustion characteristics. Process Safety and Environmental Protection, 149: 1-10. https://doi.org/10.1016/j.psep.2020.10.040
[16] Sutheerasak, E., Chinwanitcharoen, C., Ruengphrathuengsuka, W. (2019). Using diesohol and supercharging syngas on dual fuel in a turbocharging diesel-engine generator. International Journal of Mechanical Engineering and Robotics Research, 8(6): 972-976. http://doi./10.18178/ijmerr.8.6.972-976
[17] Jagtap, S., Pawar, A., Lahane, S. (2021). Effect of ethanol-biodiesel-diesel blend on performance and emission characteristics of a di diesel engine. International Journal of Heat and Technology, 39(1): 179-184. https://doi.org/10.18280/ijht.390119
[18] Pullagura, G., Bikkavolu, J., Vadapalli, S., Chebattina, K., Kuchipudi, V. (2022). Comparative study of TiO_2 nanoparticles and alcoholic fuel additives-biodiesel-diesel blend for combustion, performance, and emission improvements. International Journal of Heat and Technology, 40(5): 1249-1257. https://doi.org/10.18280/ijht.400517
[19] Abdillah, M., Amaliyah, N., Putra, A., Surahman. (2023). Biodiesel performance improvement with the addition of Al_2O_3 nanoparticles on diesel engine. International Journal of Heat and Technology, 41(2): 423-430. http://doi.org/10.18280/ijht.410217
[20] Wibowo, H., Susastriawan, A., Andrian, D. (2018). Effect of pertalite-spiritus blend fuel on performance of single cylinder spark ignition engine. IOP Conference Series: Materials Science and Engineering, 306: 012054. http://doi.org/10.1088/1757-899X/306/1/012054
[21] Saraswat, M., Chauhan, N. (2020). Comparative assessment of butanol and algae oil as alternate fuel for SI engines. Engineering Science & Technology, 23(1): 92-100. https://doi.org/10.1016/j.jestch.2019.04.002
[22] Varshini, M., Shetty, D. (2017). Experimentation on bio-kerosene stove using organic additive. AIP Conference Proceedings, 1859(1): 020105. https://doi.org/10.1063/1.4990258
[23] Basha, M., Shaahid, S., Al-hadhrami, L. (2012). Impact of fuels on performance and efficiency of gas turbine power plants. Energy Procedia, 14: 558-565. https://doi.org/10.1016/j.egypro.2011.12.975
[24] Al-Saraf, A., Al-Jumaily, S. (2013). The power enhancement of a mini-gas turbine by adding ethanol to the compressor inlet air. Al-Khwarizmi Engineering Journal, 9(4): 54-64.
[25] Al-Saraf, A., Al-Jumaily, S. (2014). Experiemntal investigation on the emission characteristics of a dual-fuel micro gas turbine by injecting ethanol into compressor inlet air. Al-Khwarizmi Engineering Journal, 10(1): 24-31.
[26] Chiariello, F., Allouis, C., Reale, F., Massoli, P. (2014). Gaseous and particulate emissions of a micro gas turbine fuelled by straight vegetable oil-kerosene blends. Experimental Thermal and Fluid Science, 56: 16-22. https://doi.org/10.1016/j.expthermflusci.2013.11.013
[27] Cavarzera, A., Morini, M., Pinelli, M., Spina, P., Vaccari, A., Venturini, M. (2014). Experimental analysis of a micro gas turbine fuelled with vegetable oils from energy crops. Energy Procedia, 45: 91-100. https://doi.org/10.1016/j.egypro.2014.01.011
[28] Silva, R., Costa, F., Lacava, P. (2019). Biofuels combustion assessment on small gas turbines. In 24th International Society for Air Breathing Engines Conference (ISABE-2019), pp. 22-27.
[29] Manigandan, S., Atabani, A., Ponnusamy, V., Gunasekar, P. (2020). Impact of additives in Jet-A fuel blends on combustion, emission and exergetic analysis using a micro-gas turbine engine. Fuel, 276: 118104. https://doi.org/10.1016/j.fuel.2020.118104
[30] Reksowardojo, I., DuongL., Zain, R., Hartono, F., Marno, S., Rustyawan, W., Putri, N., Jatiwiramurti, W., Prabowo, B. (2020). Performance and exhaust emissions of a gas-turbine engine fuelled with biojet/Jet A-1 blends for the development of aviation biofuel in tropical region. Energies, 13(24): 6570. https://doi.org/10.3390/en13246570
[31] Przysowa, R., Gawron, B., Bialecki, T., Legowik, A., Merkisz, J., Jasinski, R. (2021). Performance and emissions of a microturbine and turbofan powered by alternative fuels. Aerospace, 8(2): 25. https://doi.org/10.3390/aerospace8020025
[32] Reksowardojo, I., Duong, L., Soerawidjaja, T., Nguyen, T., Fujita O., Neonufa, G. (2022). Performance and emission characteristics of a gas turbine engine burning soap-derived biokerosene/jet A-1 blends. SAE International Journal of Fuels and Lubricants, 13(2): 125-136. https://doi.org/10.4271/04-13-02-0007
[33] Boomadevi, P., Paulson, V., Samlal, S., Varatharajan, M., Sekar, M., Alsehli, M., Elfasakhany, A., Tola, S. (2021). Impact of microalgae biofuel on microgas turbine aviation engine: A combustion and emission study. Fuel, 302: 121155. https://doi.org/10.1016/j.fuel.2021.121155
[34] Devi, B., Venkatesh, S., Vimal, R., Praveenkumar, T. (2021). Influence of high oxygenated biofuels on micro-gas turbine engine for reduced emission. Aircraft Engineering & Aerospace Technology, 93(3), 508-513. https://doi.org/10.1108/AEAT-07-2020-0150
[35] Rahim, M., Mohd Jaafar, M., Shaiful, A., Omar, W., Othman, N. (2021). Utilizing of biodiesel fuel for micro gas turbine combustion performance. AIP Conference Proceedings, 2339(1): 020235. https://doi.org/10.1063/5.0044572
[36] Iturbe-Hernández, A., Guzmán, J.,Vicente, W., Salinas-Vazquez, M. (2022). Microturbine characteristics and emissions using biofuel blends. Biofuels,13(4): 497-505. https://doi.org/10.1080/17597269.2020.1771241

[37] Alrashidi, A., Adam, N., Mohammed Ariffin, M., Fnyees, A., Alajmi, A., Abdul Aziz, H. (2022). Impact of plasma combustion technology on micro gasturbines using biodiesel fuels. Applied Science, 12(9): 4321. https://doi.org/10.3390/app12094321
[38] Aguado, R., Vera, D., Jurado F., Beltran, G. (2022). An integrated gasification plant for electric power generation from wet biomass: Toward a sustainable production in the olive oil industry. Biomass Conversion and Biorefinery. https://doi.org/10.1007/s13399-021-02231-0
[39] AlhuyiNazari, M., Alavi, M., Salem, N., El Haj Assad, M. (2022). Utilization of hydrogen in gas turbines: A comprehensive review. International Journal of Low Carbon Technologies, 17: 513-519. https://doi.org/10.1093/ijlct/ctac025
[40] Dwivedi, G., Jain, S., Sharma, M. (2011). Pongamia as a source of biodiesel in India. Smart Grid and Renewable Energy, 2(3): 184-189. https://doi.org/10.4236/sgre.2011.23022
[41] Folaranmi, J. (2013). Production of biodiesel (B100) from jatropha oil using sodium hydroxide as catalyst. Journal of Petroleum Engineering, 2013: 956479. http://doi.org/10.1155/2013/956479
[42] Banani, R., Ayadi, M., Hasine, D., Snoussi, Y., Bezzarga, M., Abderrabba, M. (2014). Biodiesel production from unrefined and refined olive pomace oil: Comparative study. Journal of Chemical and Pharmaceutical Research, 6(12): 906-915.
[43] GT 85-2-H Two Shaft Gas Turbine. Technical Handbook, Gilbert Gilkes & Gordon LTD., Kendal, 1978.
[44] Coleman, H., Steel, W. (1999). Experimentation and Uncertainty Analysis for Engineers. 2nd ed., John Wiley and Sons, New York.
[45] Exhaust emissions measurement, Recommendations for reciprocating engines and gas turbines. (1991). International Council on Combustion Engines CIMAC, 12. https://www.cimac.com/cms/upload/Publication_Press/Recommendations/Recommendation_12.pdf.
[46] Output-Based regulations: A handbook for air regulators. (2014). U.S. Environmental Protection Agency EPA, Final report. https://www.epa.gov/sites/default/files/2015-07/documents/output-based_regulations_a_handbook_for_air_regulators.pdf.

NOMENCLATURE

B	Biofuel
K	Kerosene
CO	Carbon monoxide emission, ppm
CO_2	Carbon dioxid emission, ppm
CH_3OH	Mythel alcohol (Methanol)
C_2H_5OH	Eythel alcohol (Ethanol)
HC	Unburnt hydrocarbons emission, ppm
K	Kerosene
LPG	Liquefied petroleum gas
m_F	Fuel mass flow rate, kg.s^{-1}
NaOH	Sodium hydroxide
NO_x	Netric oxides emission, ppm
P_B	Brake power, W
PM	Particle matter, mg.m^{-3}
R	Experiemntal parameter
SBK	Soap derived biokerosene
SFC	Specific fuel consumption, kg.kW^{-1}.h^{-1}
SVO	Straight vegetable oils
TiO_2	Titanium dioxide
W	Uncertainty, %
X	Independent variable