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Experimental Investigation of Performance and Emission Characteristics on Mini-scale Turbojet Engine Fueled with JetA1-Canola Methyl Ester (CME) Fuel Blends

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Abstract

The focus of this study is the experimental investigation of the effects of canola methyl ester (CME) and Jet-A1 fuel blends on performance and emissions of the mini-scale turbojet engine at different blend ratios and real flight power levels. Accordingly, $B_{2.5}$ (2.5% CME-97.5% Jet-A1), B_5 (5% CME-95% Jet-A1) and B_{10} (10% CME-90% Jet-A1) fuel blends and pure Jet-A1 fuel and power rates of taxi (7%), approach (30%), climb (85%) and take-off (100%) were tested and examined for static thrust, TSFC, EGT, emissions, noise and thermal efficiency. The results obtained show that up to 5% CME addition in turbojet engine has a maximum reduction effect of 19.6% on thrust, while this ratio is much less in partial power situations. This effect also causes an increase in the TSFC value. While the CO_2 value increased with the addition of CME, it caused a decrease in the CO and unburned HC values. However, the addition of CME caused increasing on noise level especially in taxi power state (about 7.8%), while no significant noise increase was observed in other power states. In terms of thermal efficiency, it has been observed that all fuel blends reduce efficiency in different power states, and it can be said that especially B_5 fuel blend can be used as a blend fuel in gas turbine engines at partial loads.

1. Introduction

The indispensable energy source of the aviation industry on a global scale is petroleum-based fuels. Meeting the high power needed by aircraft from another energy source does not seem possible at today's technology level. The fact that petroleum-based fuels have a high number of harmful emissions and that the petroleum resource will decrease over time in the future perspective motivates the studies for alternative fuels to meet this need.

Gas turbine engines, which operate according to the thermodynamic basis of the Brayton cycle, are used as the main power source of aircraft due to their high power/volume ratio. Although the basic structures of gas turbine engines are the same, they are divided into various types according to needs. The most important of these are Turbo-jet, Turbo-prop, Turbo-fan engines. These engines have structural changes with the needs of the aircraft. While the basic structure of a gas turbine engine is the compressor, combustion chamber and turbine. In a turbojet engine the thrust is generated as high velocity exhaust gases exit the jet nozzle. In turboprop and turbofan gas turbine engines, the energy of the exhaust gases is transferred to the shaft by means of a high-stage turbine, and thus, this shaft power is used to rotate the propellers in the turboprop engine and while a large diameter fan is rotated in the turbofan engine.

The main fuel of gas turbine engines was kerosene in the early years. Over time, kerosene-based fuels have been produced in line with the needs. The fuels of Jet-A, Jet-A1 and Jet-B are used in civil aviation, JP-4, JP-5 and JP-8 are used in military aviation.

According to estimates, it is thought that CO_2 emissions will increase by 51% in 2030 (Manigandan et al., 2020). Considering both the need for petroleum-based fuels and harmful emissions, it is essential to find natural resources that can be alternatives to petroleum-based fuels. Biologically sourced alternative fuels form the basis of research in this field. Fuels obtained from biological sources are used as additives to petroleum-based fuels, thus both a certain amount of fuel need is met from biological sources and a reduction in harmful emission gases is achieved. Vegetable oils obtained from oilseed plants, which have the most popular use as a fuel of biological origin. The use of these oils directly in gas turbine engines is not possible due to their low combustion rates (Arenas et al., 2017). For this reason, it is used as an additional fuel in engines by applying the transesterification process to the obtained biologically sourced oils (Enagi et al., 2018).

In the study of Kegl and Hribemik, it was observed that the viscosity and density of the fuel mixture increased with the addition of oil obtained from rapeseed to the fuel, while serious reductions in CO, HC and soot formation (Kegl et al., 2006). Hemighaus et al. investigated the usability of ethanol, methanol and oil methyl esters as an alternative fuel in gas turbine engines (Heminghaus et al., 2006). Manigandan et al. have shown that oxygen and fuel atomization in the fuel have serious effects on gas turbine engine performance and pollutant emissions (Manigandan et al., 2020). In this study, combustion, performance and emission parameters under different engine loads were investigated in a micro gas turbine engine by forming JET-A fuel blends with canola and sunflower oil. They showed that the biofuel blends used had a reducing effect on NO_x, CO and HC emissions. Similar results were obtained by Wang et al. and Moliere et al. (Wang et al., 2020; Moliere et al., 2009). In the study, a 50% reduction in CO emissions was observed. Biofuels obtained from jojoba and palm oil were tested by El-Zoheiry et al. and Talero et al. in a gas turbine engine at different power ratios (El-Zoheiry et al., 2020; Talero et al., 2020). In this studies with the addition of biofuel, there was a decrease in NO_x emission, while there was an increase in CO emission. It has also been observed that the use of palm oil causes serious reductions in thrust. This resulted in an increase in the amount of fuel required for a unit thrust. In their study, Chong and Hochgreb stated that due to the higher viscosity of biofuels, spray droplet structures and densities are larger, which has negative effects on fuel atomization and evaporation becomes more difficult (Chong and Hochgreb, 2014).

Within the literature review, due to the risk of damage to the turbine in gas turbine engines, much less experimental work has been done using full-size gas turbine engines (Chiaramonti et al., 2013; Habib et al., 2010; Nascimento et al., 2008; Allouis et al., 2010; Moore et al., 2017). it is possible to use alternative biological source oils in internal combustion engines, to grow canola which is an oilseed plant in non-food agricultural lands. To show the characteristics expected from jet fuels in terms of fuel properties of bio jet obtained from canola oil with Jet-A1 blends has been fundamental to focus on this study to show that it is alternative gas turbine engine fuel for the real power ratio values (taxi-approach- climb-take off) on a real mini scale jet engine.

2. Materials and Methods

2.1. Turbojet Gas Turbine Engine

Considering the high fuel consumption of gas turbine engines, the Jetcat P160 Rxi-B model, which is a mini gas turbine jet engine that can produce a maximum thrust of 160 N, was used in the study. Technical specifications of the Jet Engine are given in Table 1. And the schematic representation of the experimental setup and the experimental system in Selçuk University Civil Aviation School are given in Figure 1 and Figure 2, respectively.

Table 1. Specifications of the Jet engine used in experiments (Jetcat, 2022)

Specification	Value
Pressure ratio	3.1
Mass flow (kg/s)	0.38
Consumption Full load (ml/min)	510
Consumption idle (ml/min)	120
Weight [g]	1530
Dimensions of the diameter (mm)	112
Length (mm)	297
Compressor type	Single stage radial
Turbine type	Single stage axial
Idle rpm (1/min)	32000
Max rpm (1/min)	123000
Exhaust gas temperature (°C)	520-750
Exhaust gas velocity (km/h)	1590
Exhaust gas power output (kW)	37.5
Thrust at idle (N)	7
Thrust @ max Rpm (N)	160
SFC @ max Rpm (kg/N)	0.160

In the experiments, a flow-meter was used to determine the fuel consumption, loadcell-transmitter was used to measure static thrust, K type thermocouple was used for measurement of exhaust gas temperature (EGT), a specially designed sample probe and emission analyzer were used for determination of emission. Hall-effect rpm sensor was used for engine speed measurement and also ECU-pc and Arduino-pc hardware-software kits were used for data collection, recording and engine control. In addition, a linear roller bearing assembly used for create minimum friction ın order to measure the static thrust data without loss.

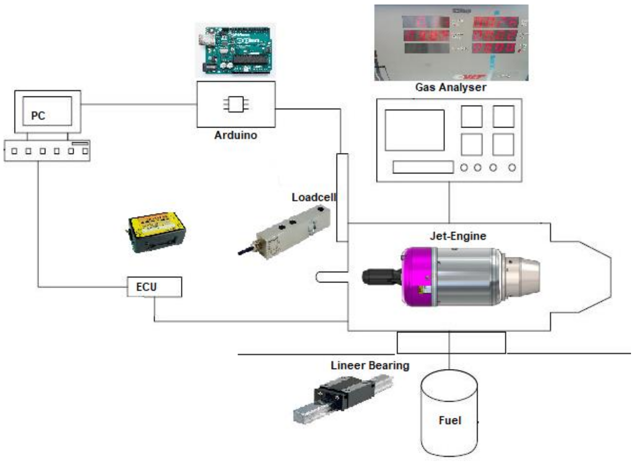

Figure 1. Schematic view of the experimental setup

In order to not to damage the jet engine during the experiments and to ensure a long life, the engine was run for 5 minutes with pure Jet-A1 fuel until the engine reached the regime temperature and after each experiment. Thus, before each experiment, the fuel system and engine met with pure Jet-A1 fuel.

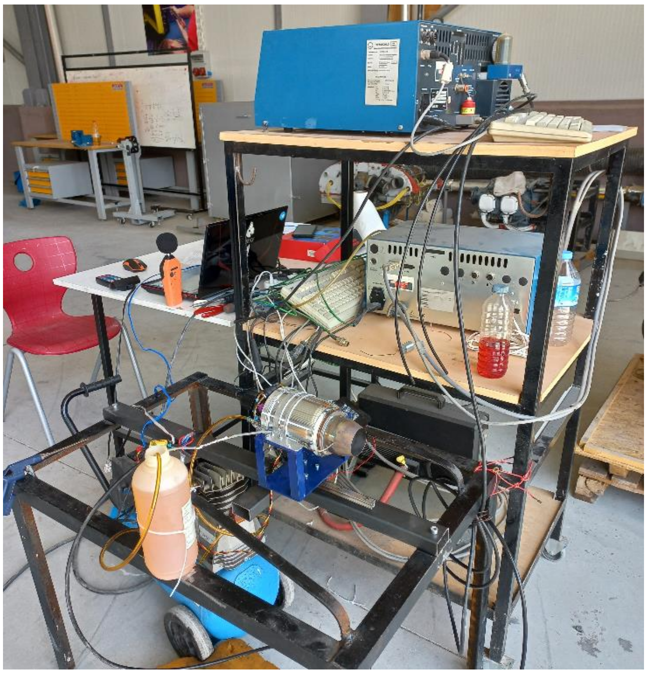

Figure 2. Experimental system of the Jet Engine

2.2. Fuel Blends Used in Experiments

Since vegetable oils have high viscosity and contain glycerine, they are not suitable for direct use in gas turbine engines. If used directly in engines, combustion will deteriorate and cause serious problems in engine performance and fuel system. For this reason, the canola oil used in the experiments was brought into the form of biofuel suitable for use in gas turbine engines by the method of transesterification (mixing, heating, washing and boiling steps). In the transesterification method, methanol is used as alcohol and KOH is used as catalyst. The important point here is that the amount of KOH used is less than 1% by weight (Aldhaidhawi et al., 2017). Otherwise, disruptions occur in the transesterification process.

Canola methyl ester (CME) and Jet-A1 fuel blends were prepared at the rates of 2.5%, 5.0%, 10% CME, considering the future production perspective of the canola plant and international legal regulations. In order to fully blend the prepared fuels, the mechanical and ultrasonic mixing technique was applied at room temperature and homogenization was achieved. The properties of Jet-A1, CME and their blends are given in Table 2.

Table 2. Properties of the Jet-A1, CME and their blends

Properties	Jet-A1	CME	$B_{2.5}$	$B_{5.0}$	B_{10}
Density (g/cm3, 15°C)	0.775	0.912	0.795	0.810	0.825
Viscosity (mm^2/s, 40°C)	1.37	3.5	1.67	2.85	3.14
Lower calorific value (kJ/kg)	42676	38492	42258	41317	40584
Flash Point (°C)	38	245	44	58	65
Freezing Point (°C)	-47	-8	-45	-42	-40
Cetane number	42	39.5	41.8	41.5	41

The addition of CME increased the densities of the fuel blends and caused a decrease in the calorific values. Besides, the addition of CME, which has a high flash point and freezing point, significantly increased the flash points and freezing temperatures of the blended fuels. However, when the properties of all blended fuels are examined, it can be said that up to 10% CME fuel addition will be suitable for use in gas turbine engines.

2.3. Experimental Procedure

In order to investigate the effects of different fuel blends on engine performance and emissions, experiments were carried out by applying the power values of the turbojet engine in real flight conditions. These power values are 7%, 30%, 85% and 100% for taxi, approach, climb and take-off, respectively. In the experiments carried out at these power values, the performance and emission measurements were recorded instantly. In addition, each experiment was repeated 3 times and the analytical average was taken.

In order to ensure the same environmental conditions in each experiment, the experiments were completed within a few days and in the same time zone. In the ambient condition measurements, it was observed that the temperature, humidity and pressure values in the environment deviated by about 1% during the experiments. Before starting the engine experiments, the jet engine was run with pure Jet-A1 fuel in idle state for 5 minutes. Thus, both the engine is heated and the fuel system is purified from the Jet-A1-bio fuel blends. Then the prepared fuel blend was given to the engine. When it was ensured that the fuel system was completely filled with the new blend fuel after a fixed 1-minute operation, experiments were carried out for different power values and measurements were taken. Before each experiment, the initial test conditions were met by running for 5 minutes with pure Jet-A1 fuel.

Even if the measurement values are recorded instantly, measurement uncertainties occur due to various reasons such as measurement equipment, environmental conditions and human errors. For this reason, it is necessary to evaluate the measurement results together with uncertainty analysis. We can generally define the uncertainty that occurs for all measurements with the following Equation 1 (Holman, 2001). The measurement uncertainties calculated using Equation 1 are presented in Table 3.

$$w_R = \pm\left[\left(\frac{\partial R}{\partial x_1} w_{x_1}\right)^2 + \left(\frac{\partial R}{\partial x_2} w_{x_2}\right)^2 + \left(\frac{\partial R}{\partial x_3} w_{x_3}\right)^2 + \ldots\ldots + \left(\frac{\partial R}{\partial x_n} w_{x_n}\right)^2\right]^{1/2} \quad (1)$$

Table 3. Uncertainties of the experimental results

Parameter	Uncertainty
Static thrust (N)	±0.019
Fuel consumption (ml/min)	±0.020
EGT (ºC)	±0.001
Carbon monoxide (% Vol)	±0.002
Carbon dioxide (%Vol)	±0.002
Hydrocarbon (ppm)	±0.020
Noise level	±0.024

When the uncertainty analysis results were examined, it was seen that the measurement uncertainty values were sufficient for the experimental measurements and the data collected and the experiments were carried out.

In addition, the thermal efficiency of the turbojet engine, which is the ratio of the exhaust kinetic energy to the heat content of the fuel used, was calculated by Equation 2 using the exhaust gas output velocities measured from the experiments.

$$\eta_{th} = \frac{(1+f)\frac{V_e^2}{2}}{fQ_R} \qquad (2)$$

In this equation, Q_R is the heat value of the fuel, V_e represents the exhaust velocity, and f is the fuel/air ratio. These data needed for calculation are transferred to the computer software by means of the electronic control unit of the jet engine. In a jet engine operating according to the Brayton cycle, the thermal efficiency is expected to be between 2.2% and 5% at small compression ratios obtained with a single-stage turbine according to calculations (Patricio and Tavares, 2010).

3. Result and Discussion

To investigate the usability of bio derived fuels like $B_{2.5}$ (97.5% Jet-A1, 2.5% CME), B_5 (95% Jet-A1, 5% CME), B_{10} (90% Jet-A1, 10%CME) as aviation fuel, the effects of fuel blends on jet engine performance and emissions were investigated. In addition, comparisons were made by performing experiments with pure Jet-A1 fuel.

3.1. Static Thrust

Static thrust measurements were performed by operating the jet engine for different flight power conditions for each fuel blend and pure Jet-A1 fuel. Obtained static thrust values are given in Figure 3.

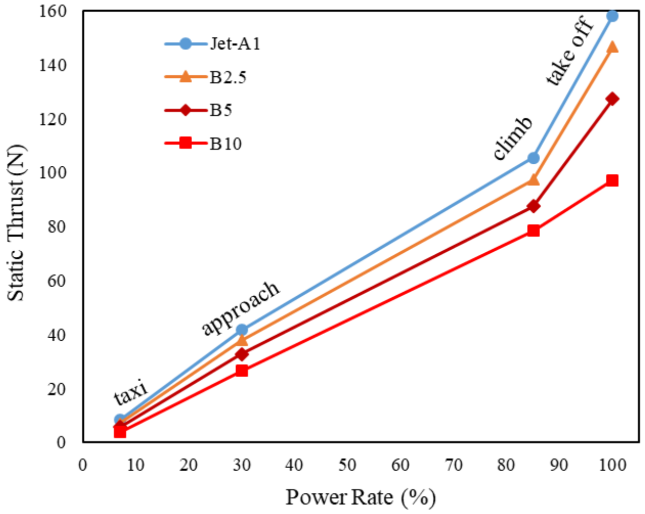

Figure 3. Static thrust developed as a function of engine power loads for fuel blends

When the Figure 3 is examined, the maximum thrust reduction occurs as 25.71% for B_{10} fuel in partial power situations, while this decrease is 38.61% for the same fuel blend at full power. Thrust reduction for B_5 fuel is 17.1% at partial loads and 19.6% at full power. The reason for this decrease in thrust can be explained by the delay in combustion at high engine speeds. The difficulty in evaporation as the biofuel ratio in the fuel blend increases, the inability to complete the combustion event in the combustion chamber with the prolonged combustion time, and the decrease in the exhaust velocity as the energy of the fuel continues to be released after the exhaust nozzle by continuing after the turbine.

3.2. Thrust Specific Fuel Consumption (TSFC)

The amount of fuel required to generate 1N thrust in aircraft engines is called thrust specific fuel consumption (TSFC). TSFC values were obtained for different fuel blends at different power states are given in Figure 4.

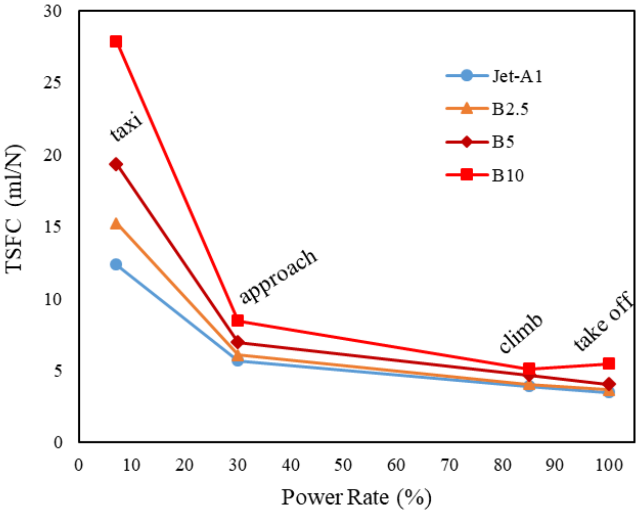

Figure 4. Thrust specific fuel consumptions as a function of engine power loads for fuel blends

When Figure 4 is examined, the amount of fuel required for unit thrust decreases as the speed increases, in accordance with the characteristics of the jet engine. This situation is seen similarly for all fuel blends. However, as the biofuel ratio increases, there is a significant increase in the fuel consumption required for the unit thrust, especially for the taxi situation. This is due to the decrease in the calorific values of the biofuel blends and the combustion delay, and the combustion not taking place in accordance with the engine characteristics. In addition, it is seen that the increase in TSFC values at higher partial power conditions and at full power the maximum increase is around of 36%.

3.3. Exhaust Gas Temperature (EGT)

Exhaust gas temperatures for the different fuel blends tested are given in Figure 5. A decrease in EGT value was observed at all power levels except the Taxi situation. This decrease was 2% for approach, 1.6% for climb and 7.3% for takeoff. The reason for this decrease in the exhaust gas is due to the fact that the combustion characteristics of bio jet fuel are worse than that of Jet A1 fuel, and therefore the combustion chamber temperatures are low.

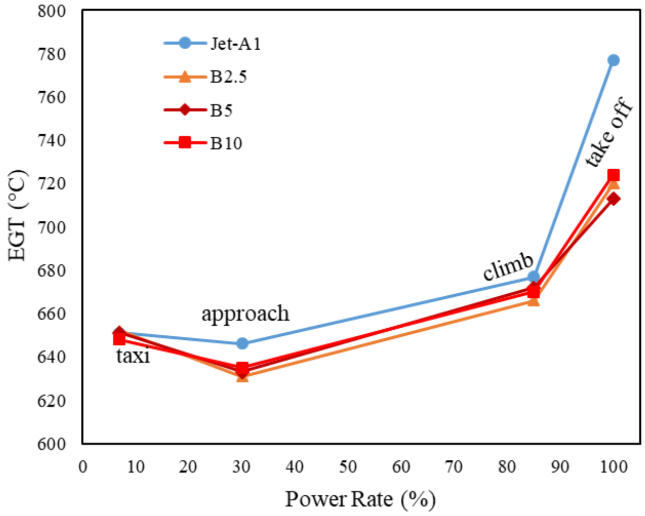

Figure 5. Exhaust gas temperature as a function of engine power loads for fuel blends

The EGT values for all fuels varied between 631 °C and 777 °C from taxi to takeoff power levels. While EGT is lower at low power loads, and increase with the increase of power levels. High EGT value means high energy exhaust gas fluid, that is, higher thrust. This shows that at the same power level, higher temperature will create more thrust. However, in terms of material strength, exceeding the design temperatures will seriously reduce the engine life.

3.4. Emission Measurements

In internal combustion engines such as turbojet engines, carbon dioxide (CO_2) and water vapor (H_2O) occur mainly in the end products of combustion (Turns, 2000). Besides, other emission parameters like carbon monoxide (CO) and unburned hydrocarbons (HC) showing how the combustion occurs physically and chemically. The presence of CO and HC in the end of combustion products is the most basic indicator that the combustion is not fully realized. If the combustion were theoretical complete, these emissions would not be included in the end products of combustion and only the basic emissions, CO_2 and H_2O, would occur. In Figures 6, 7 and 8, CO_2, CO and HC emissions are given for different power levels, respectively.

As the amount of CME in the fuel mixture increases, the CO_2 emission increases. Although this situation is seen in all power levels as seen in Figure 6. The CO_2 emissions are approximately the same for Jet-A1 and $B_{2.5}$ fuels, especially at high power levels. The opposite situation is seen for CO emission in Figure 7. The increase in CME in fuel mixtures causes a decrease in CO emissions. This is explained by the improvement of combustion, which is associated with the high amount of O_2 in the CME, as in all biofuels.

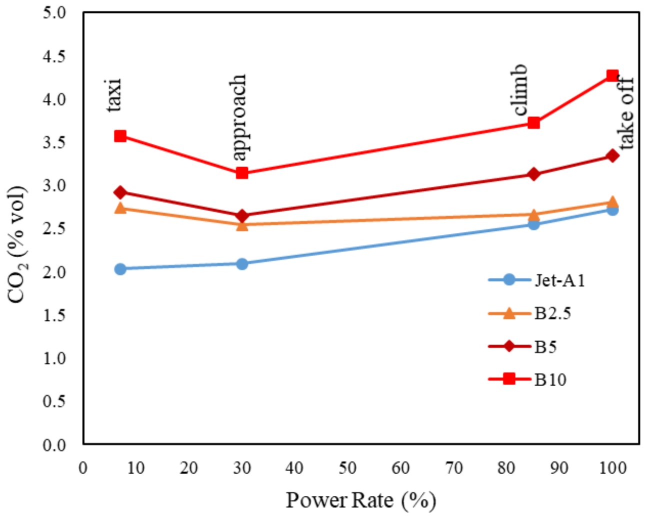

Figure 6. The effect of biojet blends at different power ratios on CO_2 emission

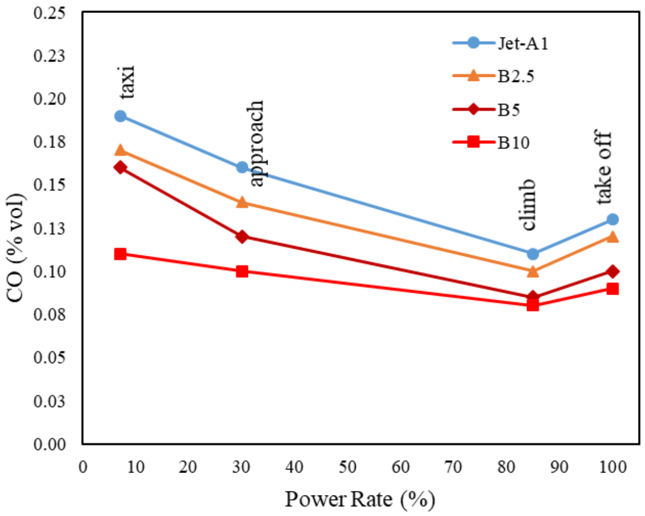

Figure 7. The effect of biojet blends at different power ratios on CO emission

However, as can be seen in Figure 7, the decrease in the amount of CO valid for all fuel mixtures increased for all fuel mixtures at high power cycles. This can be explained by the relative deterioration of the combustion phenomenon, especially at load power cycles, and the insufficient time required for combustion.

When Figure 8 is examined, there is a decrease in unburned HC emissions at all power levels. This is associated with increased CO_2 and reduced CO emissions, as a result of more efficient combustion of fuel blends. In addition, a decrease in the HC decreasing trend was observed at high power levels. This is explained by the decrease in combustion efficiency at high engine speeds.

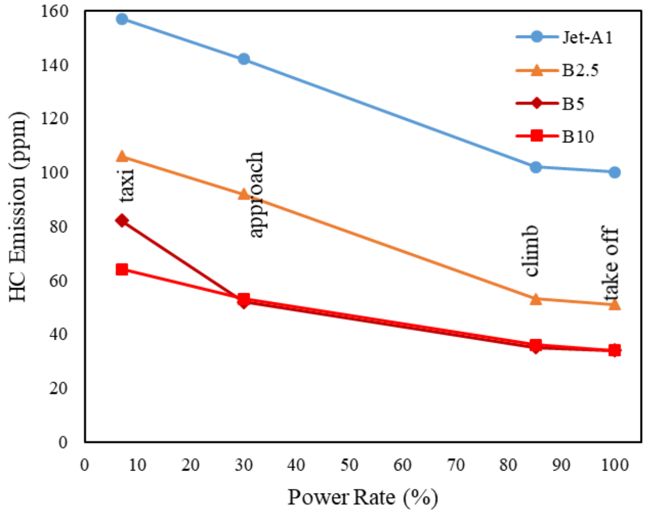

Figure 8. The effect of biojet blends at different power ratios on HC emission

3.5. Noise Emission

Noise emission is mostly produced by turbojet engines among gas turbine engines. Due to its nature, high-speed jet exhaust flow brings high sound levels and poses a problem for high-speed passenger and military aircraft using turbojet engines. For this reason, measurement of sound levels for different fuels is a necessity. Figure 9 shows the sound level (noise) values released from the turbojet engine of the fuel blends at different power levels.

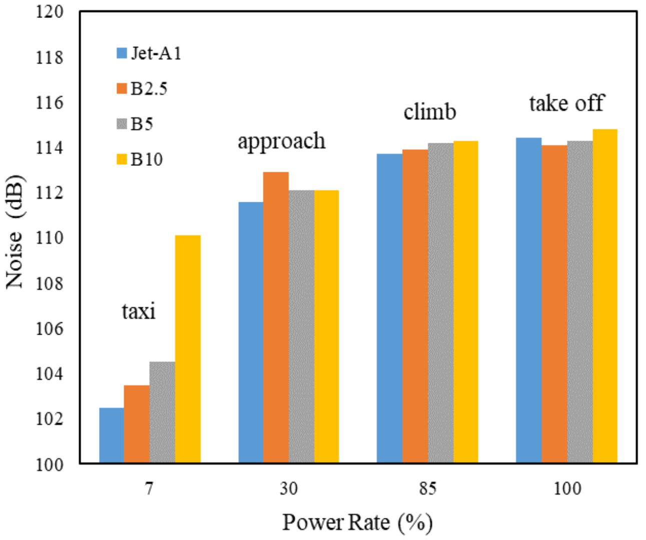

Figure 9. The effect of biojet blends at different power ratios on noise levels

When Figure 9 is examined, it is seen that the increase in the CME ratio in the fuel blend increases the noise, especially in the case of taxi, and the maximum increase is 7.8% in the B_{10} fuel. When looking at other power levels, it is seen that the noise levels are very close to each other for fuel blends, with a maximum deviation of 1.1%.

3.6. Thermal Efficiency

Thermal efficiency is one of the parameters that shows the conversion of the chemical energy of the fuel into kinetic energy with taking into account of the thermodynamic cycle efficiency. Kinetic energy consists of the exit velocity of the exhaust gases in accordance with the characteristics of the jet engine. In Figure 10, the thermal efficiency for different fuel blends is given for different load conditions.

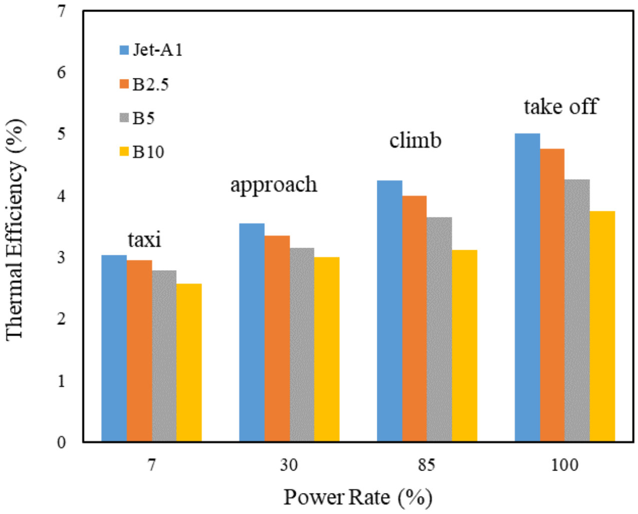

Figure 10. The effect of biojet blends at different power ratios on thermal efficiency

As seen in Figure 10, the thermal efficiency decreases with the addition of CME in all load cases. Since the thermal efficiency is expressed as the ratio of the kinetic energy of the exhaust gases to the thermal value of the fuel, the decrease in the calorific values in Table 2 is expected to increase the thermal efficiency, while the rapid decrease in the output velocity of the exhaust gases caused a decrease in the thermal efficiency. In other words, this is due to the fact that the decrease in the exhaust gas velocity with the addition of CME occurs faster than the decrease in the calorific values of the fuel blends. For this reason, the decrease in thermal efficiency occurred more at take-off than at partial loads.

4. Conclusion

The rapid development of aviation in the world and the dependence of the aviation industry on internal combustion engines cause the demand for petroleum and petroleum-derived fuels to increase gradually, despite the decrease in their reserves. In the future perspective, a part of the fuel need of the aviation industry is met by a small rate of bio-based fuels, which corresponds to large amounts of fuel. The findings obtained in this study, which was carried out as a part of the search for alternative gas turbine engine fuels in terms of performance and emissions, can be summarized as follows;

- Up to 5% CME addition in turbojet engine has a maximum reduction effect of 19.6% on thrust, while this ratio is much less in partial power situations. B_5 is a suitable fuel for partial load situations without exceeding 5% as an alternative fuel addition, as there is a significant reduction in thrust when the CME addition is greater than 5%.

- It has been observed that the addition of CME causes significant increases in TSFC value at partial power conditions (especially before 30% power rate).

- Exhaust gas temperatures decreased with the addition of CME for all power states. While this situation is welcomed in terms of material strength, it creates a disadvantage for the thrust due to the kinetic energy of the gases.

- With the addition of CME, there was an increase in CO_2 emissions in all power situations, while there was a decrease in CO and unburned HC emissions. This shows that the combustion is improved with O_2 in the CME and the addition of CME has a positive effect on combustion and emissions.

- It was observed that the addition of CME increased the noise emission, especially in the case of taxi (7% power) and this increase was 7.8%. In all other power conditions, the noise increase was below 1.1%. This shows that the addition of CME does not cause a significant increase in noise emissions, especially for jet engines with high noise levels.

- A reduction in thermal efficiency is observed at all power states for all fuel blends. While it is thought that the reduction of the fuel specific heats with the addition of CME will increase the thermal efficiency, the deterioration in the combustion characteristics reduces the kinetic energy of the exhaust gases faster. This resulted in a decrease in thermal efficiency.

Nomenclature

CME	Canola methyl ester
TSFC	Thrust specific fuel consumption, ml/N
CO_2	Carbon dioxide, %vol
CO	Carbon monoxide, %vol
O_2	Oxygen
HC	Hydro carbon (ppm)
EGT	Exhaust gas temperature °C
Ecu	Electronic control unit
η_{th}	Thermal efficiency

Ethical approval

Not applicable.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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