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Experimental Evaluation of Methanol/Jet-A Blends as Sustainable Aviation Fuels for Turbo-Engines: Performance and Environmental Impact Analysis

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Abstract: This study offers a comprehensive examination, both theoretically and experimentally, of the potential of methanol (M) as a sustainable aviation fuel (SAF) assessed in combination with kerosene (Ke—Jet-A aviation fuel + 5% Aeroshell oil). Different blends of methanol and kerosene (10%, 20%, and 30% vol. of (M) was added to Ke) were tested in an aviation micro turbo-engine under various operating regimes, such as idle, cruise, and maximum. Key engine parameters, including combustion temperature, fuel consumption, and thrust, were closely monitored during these trials. Essential performance indicators such as combustion efficiency, thermal efficiency, and specific consumption for all fuel blends under maximum operating conditions are also presented. Physical and chemical characteristics, such as viscosity, density, calorific value and flash point, were determined for each blend. Moreover, elemental analysis and FTIR spectroscopy were utilized to evaluate the chemical composition of the fuels. This study further investigated the air requirements for stoichiometric combustion and computed the resulting CO_2 and H_2O emissions. Experimental tests were conducted on the Jet Cat P80® micro turbo-engine, covering assessments of starting procedures, acceleration, deceleration, and pollutant emissions (CO and SO_2) during various engine operating conditions. The results suggest that the examined fuel blends demonstrate stable engine performance at concentrations of 10% and 20% methanol. However, observations indicate that with an increase in methanol concentration, particularly at 30%, the stability of the engine at idle and, notably, at maximum speed decreases significantly. Specifically, at a 30% methanol concentration, the engine no longer operates stably, exhibiting significant rpm fluctuations, leading to the decision not to explore higher concentrations.

Keywords: methanol; kerosene; aviation; turbo-engine; fuel; sustainability

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1. Introduction

Amidst a growing emphasis on environmental sustainability, the aviation industry has turned its attention to alternative fuels like methanol. Several experimental studies have been undertaken to evaluate the feasibility, performance, and environmental impact of methanol-based aviation fuels. A systematic analysis of the latest research findings, methodologies, and advancements in this field underscores the potential of methanol as a viable alternative to conventional jet fuels. This has led to the conclusion that the aviation industry is actively seeking sustainable alternatives to traditional fossil fuels to mitigate environmental impacts. Methanol, recognized for its versatility as a liquid fuel, has emerged as a promising candidate owing to its renewable properties.

Numerous studies have delved into the production methods of methanol, with a focus on sustainable pathways such as biomass and carbon capture utilization. Discussion on the chemical and physical properties of methanol relevant to aviation applications lays the groundwork for understanding its behaviour as a fuel. A comprehensive review of experimental methodologies employed to evaluate methanol-based aviation fuels, including engine performance tests, emissions analysis, combustion characteristics, and material compatibility, has been undertaken in recent studies. Various experimental setups, ranging from laboratory tests to real-flight simulations, have been explored, highlighting the diversity of research approaches. These studies cover parameters such as thermal efficiency, power output, combustion stability, and emissions profiles, including nitrogen oxides (NOx), particulate matter (PM), and carbon dioxide (CO_2). Comparative analyses with traditional jet fuels are discussed to assess the viability of methanol as a drop-in replacement. Additionally, environmental impact assessment is conducted, considering factors such as life cycle analysis, carbon footprint, and sustainability metrics.

The challenges associated with the widespread adoption of methanol-based aviation fuels are also addressed, including production scalability, infrastructure requirements, and policy implications. Potential solutions and ongoing research efforts aimed at overcoming these challenges are highlighted. Future perspectives on research directions and industry adoption are also presented. Thus, the environmental implications and technological strategies associated with methanol production from biomass sources, which examines the state of the art in methanol production, emphasizing its environmental footprint and the diverse methods employed for its synthesis, was made within [1]. The study assesses the environmental impacts of various biomass-to-methanol conversion technologies, considering factors such as greenhouse gas emissions, energy consumption, and resource depletion. Through a detailed analysis, the paper highlights these environmental aspects in the context of sustainable methanol production. Furthermore, the review elucidates the technological approaches utilized in the conversion of biomass to methanol. This includes an in-depth exploration of cutting-edge techniques and advancements in the field, providing valuable insights into the current state of research and development. The paper not only synthesizes existing knowledge but also identifies key research gaps and areas that require further exploration for the sustainable production of methanol from biomass.

Other studies, such as ref. [2], conduct a rigorous experimental study to explore the feasibility and performance of methanol–diesel blends as fuels. Focusing on an diesel engine, the research investigates the effects of incorporating methanol into diesel fuel, aiming to assess combustion efficiency, emissions, and overall engine performance.

The study involves detailed experimentation, utilizing a range of methanol–diesel blends. Through comprehensive analyses, including combustion stability assessments, thermal efficiency measurements, and emission profiling, it systematically evaluates the impact of methanol–diesel blends on engine operation.

Methanol is a promising energy carrier, with approximately 90 billion liters produced annually worldwide. The production mainly involves coal gasification and steam methane reforming of natural gas. Integrating methanol production into existing facilities like pulp and paper mills or power plants can establish nearly carbon dioxide (CO_2)-neutral closed-loop systems [3,4].

Green methanol, which is carbon-neutral, is produced by combining CO_2 and hydrogen. This process uses renewable electricity-derived hydrogen and biogenic CO_2. It helps mitigate CO_2 emissions by utilizing captured CO_2 from various sources and repurposing it as a valuable resource, contributing to sustainable industrial practices [4,5].

In methanol synthesis, unwanted products like H_2O and waste heat can be efficiently harnessed to produce H_2 in a recirculating system. Green methanol is easy to transport, store, and distribute, though precautions are needed to prevent corrosion and adverse effects on certain materials due to its chemical properties [6].

Methanol production incorporating carbon capture and utilization (CCU) techniques is being explored. Studies systematically evaluate the environmental impact of these processes, quantifying greenhouse gas emissions, energy consumption, and other environmental indicators, providing valuable insights for sustainable chemical manufacturing [7,8].

International Air Transport Association (IATA), in 2023, provided a comprehensive and critical examination of sustainable aviation fuels (SAFs) [9]. This is a vital resource, offering an in-depth analysis of the current landscape, challenges, and opportunities related to SAFs. It critically evaluated the feasibility and scalability of SAF production methods, emphasizing key technological advancements and innovations in the field. Moreover, the paper delved into the economic viability and policy frameworks necessary to facilitate the widespread adoption of SAFs in the aviation sector.

Reference [10] provides a comprehensive techno-economic analysis of biomass gasification processes for methanol production. The study evaluates the economic feasibility and technological viability of producing methanol from biomass feedstocks, covering aspects ranging from feedstock selection and gasification processes to methanol synthesis. It quantifies capital costs, operational expenses, and overall production efficiency across different process configurations and technological advancements.

In a related publication, the Federal Aviation Administration (FAA) released FAA Advisory Circular AC 150/5230-4B in 2023 [11], offering a detailed set of guidelines and procedures for the safe handling and quality control of aviation fuels. This advisory circular serves as a foundational reference for professionals in the aviation industry, ensuring adherence to stringent safety and quality standards in fuel management practices.

The utilization of alcohols in aviation turbo-engines remains a subject of controversy, yet several studies have ventured into examining their feasibility and performance in this domain. Initially, tests and certifications were conducted on ethanol/AVGAS blends for aviation piston engines [12], with subsequent exploration involving ethanol/Jet-A mixtures on piston aviation engines [13]. The adoption of a new controller type demonstrated the engine's capability to overcome certain operational limitations.

Further investigations have explored the introduction of butanol/Jet-A mixtures to piston aviation engines, uncovering benefits over ethanol concerning physical–chemical properties and performance, as well as reduced concentrations of gaseous pollutants compared to traditional aviation fuel [14,15]. Additionally, research has investigated the use of ethanol as an environmentally friendly fuel for small gas turbine engines in controlled laboratory environments, evaluating various ethanol and Jet-A-1 mixtures and their effects on engine parameters [16]. Notably, bioethanol blends with Jet-A fuel were subjected to testing using the JET Cat P80® micro turbo-engine (GUNT Hamburg, Germany), with careful monitoring of engine parameters across various operational conditions [17].

Regarding power engineering, studies have examined the biofuels' effects and blends derived from alcohol on gas turbines, revealing diverse effects on emissions such as increased carbon monoxide (CO) levels alongside significant reductions in nitrogen oxides (NOx) and particulate matter (PM10) [18]. Given the varied effects observed in combustion from alcohol and JET-A-1 mixtures, methanol was selected as the experimentation alcohol as an alternative fuel in microturbojet engines, an area with limited exploration.

A gap in the literature has been identified regarding the use of alcohols in turbine engines, particularly the utilization of methanol in aviation turbine engines. Additionally, the study of transient processes, such as startup, acceleration, and abrupt deceleration, in advanced micro turbo-engines fueled with blends of kerosene and methanol in various proportions, has not been identified in the literature.

The novelty of this study lies in the investigation of the effects of kerosene–methanol blends in an aviation microturbine engine.

This study aims to evaluate the aviation micro turbo-engine operational parameters, commonly used for drones or aero models, when fueled with different blends of kerosene and methanol. A comparative analysis of fuel blends comprising Jet-A + 5% Aeroshell 500 Oil (Ke) with 10%, 20%, and 30% methanol is conducted, with Ke serving as the reference fuel. Moreover, given the polarity of the methanol, its miscibility with Jet-A is very low, thus leading to problems related to the homogeneity of the blend. But in order to overcome the issue of methanol polarity and its miscibility problem, simple stirring of the liquids ensures a relative homogeneity, making the blend suitable for use.

This research provides a fresh perspective on the potential of these alternative fuel blends, assessing their performance concerning efficiency, emissions, and behavior under various operational conditions. The findings obtained could contribute to the development of more sustainable and energy-efficient technologies in aviation. Additionally, it addresses a gap in the literature concerning the testing of methanol in turbine engines.

2. Materials and Methods

Fuel blends of kerosene + 10% methanol, kerosene + 20% methanol, and kerosene + 30% methanol were prepared and were subjected to burning in a turbo-engine, and all the tests described below were performed.

2.1. Analysis of the Fuel Blends

Physical–chemical properties of the fuels and blends used for testing were determined as follows:

Density Measurements

The density of all investigated fuel blends was determined in accordance with SR EN ISO 3675/2002 [19].

Flash Point Measurements

Flash points, which denote the minimum temperature at which the vapors of substances ignite when exposed to a flame, were determined for Jet-A fuel, methanol, and all tested fuel blends as outlined in ASTM D92 [20].

Kinematic Viscosity Measurements

Kinematic viscosity measurements were performed for Jet-A fuel at 40 °C, methanol, and all tested fuel blends, as experimentally determined following the procedures outlined in SR EN ISO 3104/2002 [21].

Low Calorific Value Determination

The low calorific value of Jet-A fuel, methanol, and all fuel blends was experimentally determined following ASTM D240-17 guidelines [22].

FTIR Analysis (Fourier Transform Infrared Spectroscopy)

FTIR analysis was conducted for all samples using a Spectrum Oil Express Series 100, v 3.0 spectrometer from Perkin Elmer (Waltham, MA, USA), equipped with specialized software for fuel blend analysis.

Elemental Analysis

An elemental analysis was conducted for Jet-A fuel, methanol, and all tested fuel blends; the main elements of the fuels (C, N, H, and O) were assessed to determine their percentage of carbon, hydrogen, nitrogen, and oxygen content, following the procedure outlined in ASTM D 5291-16 [23].

2.2. Fuel Blend Combustion

After establishing the elemental analysis of all fuel blends, calculations were conducted to determine the minimum air quantities required for stoichiometric combustion. Accurate calculations of resulting water and CO_2 emissions facilitate a thorough assessment of gaseous pollutant generation during combustion. Consequently, it was observed that the examined fuel blends yield reduced levels of gaseous pollutants in comparison to conventional combustion methods.

2.3. Combustion Tests

The experimental setup, methodologies, equipment, and testing protocol are detailed in the subsequent section. The experiments were carried out utilizing a Jet CAT P80® turbo-engine [24], illustrated in Figure 1.

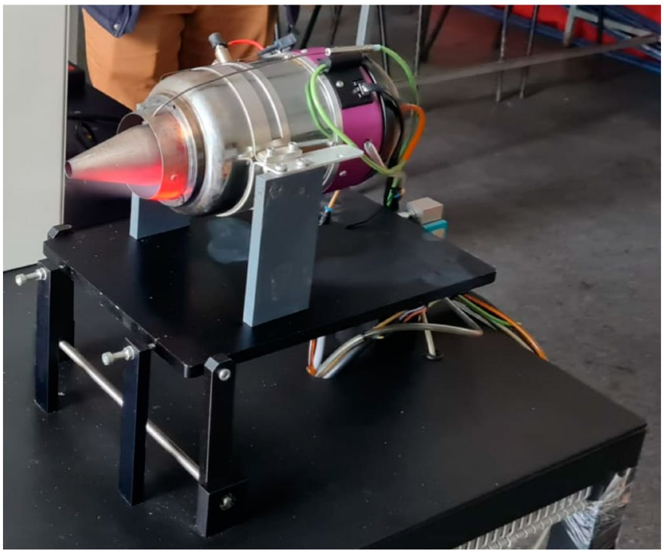

Figure 1. The instrumentation setup for the test bench.

This section investigates the influence of different fuel blends on the performance of a turbocharged engine. The fuel blends under scrutiny comprise kerosene mixed with varying proportions of methanol (10%M, 20%M, and 30%M), with each blend supplemented with 5% of Aeroshell 500 oil for engine lubrication, given the absence of a dedicated lubrication system in such a small engine. The experiments were carried out across three different operational modes: idle regime (18.7% throttle gas), cruise regime (30% throttle gas), and maximum regime (94% throttle gas—this for safety reasons). Each mode underwent testing for approximately 2 min, during which engine parameters were meticulously monitored. The parameters measured were the following: temperature (Tcomp) after the compressor, temperature (Tcomb) in front of the turbine, fuel flow (Qf), air flow, pressure in the combustion chamber, and thrust (F). Despite variations in fuel blends, the turbocharged engine consistently maintained its shaft speed throughout the experiments; various fuel blends were introduced into the combustion chamber in different proportions to sustain this consistent speed. Despite these variations, the compressor operated steadily throughout the experiments, leading to consistent airflow and uniform pressure downstream of the compressor. Under conditions of constant shaft speed, comparative evaluations were conducted for parameters such as fuel consumption (Qf), temperature in front of the turbine (Tcomb), and thrust (F).

2.4. Gaseous Emissions Measurements

Measurements of gaseous emissions were performed utilizing the MRU Vario Plus analyzer (Messgeräte für Rauchgase und Umweltschutz GmbH, Neckarsulm-Obereisesheim, Germany), as depicted in Figure 2. Concurrently, measurements of gas components such as O_2, CO, NO, NO_2, NOx, SO_2, and CH_4 were conducted.

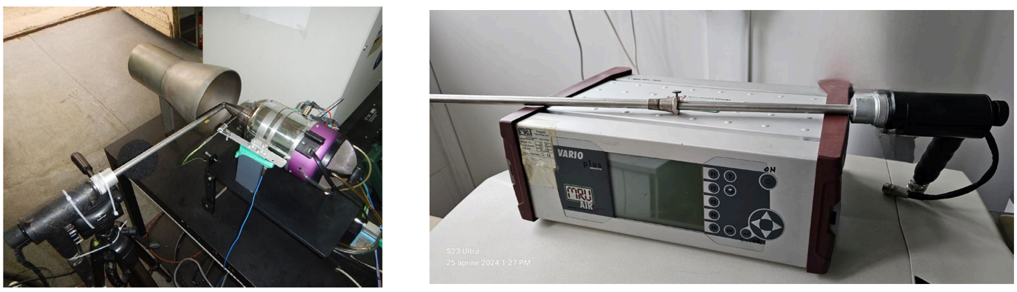

Figure 2. MRU analyzer.

3. Results

3.1. Experimental Results for the Physical–Chemical Properties of Fuel Blends

The collected measurements for all samples are tabulated and presented in Table 1.

Table 1. Experimental results of the physical–chemical properties of fuel blends.

Sample	Flash Point °C	Kinematic Viscosity at 40 °C cSt	Density at 22 °C g/cm^3	Low Calorific Value MJ/kg	Elemental Analysis [%]
Ke (Jet-A+5%Aeroshell 500)	42.3	1.39	0.817	42.39	C = 85.17 H = 13.31 N = 0.07 O = 1.45
Ke+10%M	23.7	1.31	0.815	40.15	C = 80.40 H = 13.23 N = 0.06 O = 6.3
Ke+20%M	23.4	1.22	0.812	37.9	C = 75.63 H = 13.14 N = 0.06 O = 11.15
Ke+30%M	23.3	1.14	0.810	35.66	C = 70.85 H = 13.06 N = 0.05 O = 16
M	11.8	0.545	0.792	19.97	C = 37.45 H = 12.48 N = 0 O = 49.94

It is worth mentioning that the low calorific value and elemental analysis were specifically determined only for Jet-A fuel. As for the tested fuel blends, these parameters were calculated based on reference values [25–27].

A thorough analysis of the data provided in Table 1 yields several significant conclusions:

- The trend observed in the flash point, kinematic viscosity, and density indicates a decrease with higher alcohol concentration. This relationship suggests a notable influence of the alcohol content on these physical properties.
- The decrease in low calorific value with increasing alcohol concentration implies an undesirable characteristic. This observation warrants further investigation into its implications for combustion efficiency.
- Elemental analysis indicates that as alcohol concentration increases, carbon and hydrogen content decrease, while oxygen content increases. This implies a possible decrease in the resulting CO_2 concentration during the combustion process, ascribed to a diminished requirement for oxygen.
- Analysis of all investigated fuel blends shows consistent patterns. The kinematic viscosity at 40 °C, flash point, and low calorific value decrease proportionally as the alcohol percentage increases. This consistency underscores the predictable impact of alcohol concentration on these properties.
- Elemental analysis further indicates that the increase in alcohol percentage corresponds to a rise in oxygen content and a decrease in carbon content. These findings enhance our understanding of the elemental composition changes caused by varying alcohol concentrations in fuel blends.
- FT-IR spectroscopy emerges as a valuable tool for evaluating chemical modifications within a substance. The incorporation of alcohols or biodiesel into conventional aviation fuel leads to alterations in its chemical composition. Figure 3 depicts the FTIR

spectra for kerosene, Ke+10% methanol, Ke+20% methanol, Ke+30% methanol, and 100% methanol.

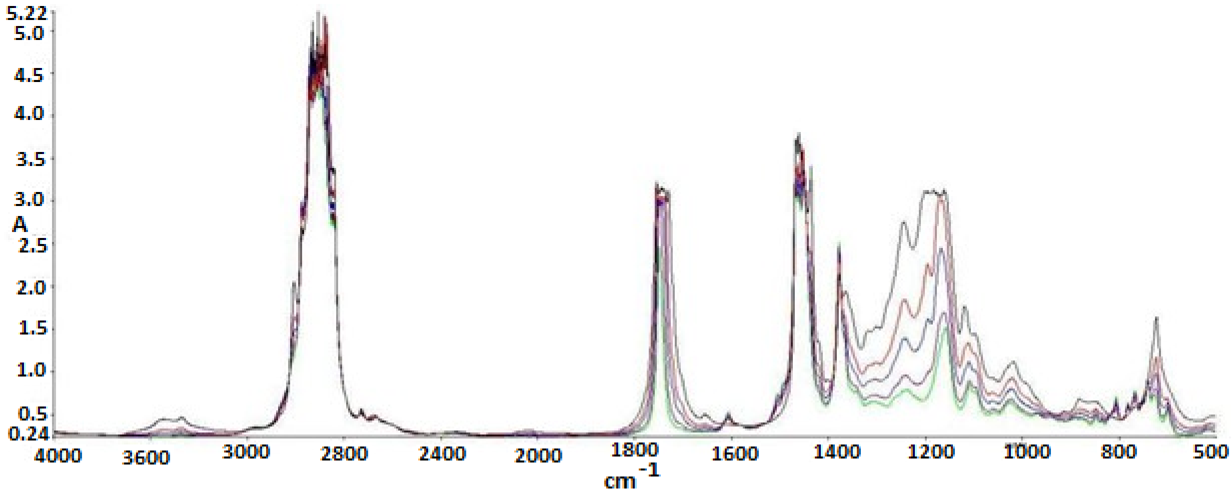

Figure 3. FTIR spectra of Ke, Ke+10%M, Ke+20%M, Ke+30%M, and 100% M (black: Ke, red: Ke+10%M, blue: Ke+20%M, purple: Ke+30%M, green: 100%M).

As can be seen in Figure 3, the main differences between the spectra of the regular aviation fuel (Ke) and the blends are at 3200–3600 cm^{-1}, meaning that hydroxyl (-O-H) has been brought into the structure. As expected, the higher the alcohol concentration, the higher the peak. Another important modification appears at 1750 cm^{-1}, representing the presence of oxygen bonded by a C atom (C-O). At 1450 cm^{-1}, the presence of methylene groups (–CH_2) are shoving a slight decrease compared with Ke. The radiation absorbed at 1350 cm^{-1} is showing an increase in methyl groups (–CH_3). Another large difference is shown at 1000 cm^{-1}, representing the C-OH bond. As in the case oh –OH, as the concentration of the alcohol increases, C-OH increases [28].

3.2. Combustion Reaction Analysis

To understand the properties of the stoichiometric combustion of various fuel blends, it is essential to grasp their elemental composition. This study specifically targets hydrocarbons with the general formula CcHhOoNn [29,30], with specific fractions of gC, gH, gO, and gN outlined in Table 1.

Determining the necessary oxygen quantity for stoichiometric combustion is crucial for gaining insights into the combustion process and fostering a comprehensive understanding of the chemical reactions involved. This is computed using Equation (1).

$$M_o = \frac{32}{12gC} + \frac{32}{4gH} - \frac{32}{32gO} = 2.667gC + 8gH - gO \quad (1)$$

$$M_{air} = 4.35M_o \quad (2)$$

The resulting CO_2 and H_2O from the combustion reaction are as follows:

$$CO_2 = 44\frac{gC}{12} \quad (3)$$

$$H_2O = 9gH \quad (4)$$

The results are presented in Table 2, based on Equations (1)–(4).

Table 2. Values for 1 kg of fuel blend.

Blend	MO [kg]	M_{air} [kg]	CO_2 [kg]	H_2O [kg]
Ke+5% Aeroshell 500Oil	3.32	14.45	3.12	1.20
Ke+10%M	3.14	13.66	2.95	1.19
Ke+20%M	2.96	12.86	2.77	1.18
Ke+30%M	2.77	12.07	2.60	1.18
M	1.50	6.52	1.37	1.12

An inverse relationship is observed between the required air quantity and alcohol concentration. This trend is attributed to the increase in oxygen content associated with higher alcohol concentrations. Moreover, there is a proportional decrease in CO_2 concentration noted with increasing alcohol concentration. Indeed, these observations emphasize the complex relationship between alcohol content, oxygen levels, and the resulting concentration of carbon dioxide during the stoichiometric combustion process.

3.3. Micro Turbo-Engine Test Bench Experiments

As can be assessed in Figure 4, the polar nature of the methanol makes it hardly miscible with kerosene. Therefore, in order to avoid the separation of the two phases, the fuel fed to the Jet Cat turbo-engine was constantly stirred.

(**a**) (**b**)

Figure 4. The separation of methanol and kerosene: (**a**) the separation of the two liquids, (**b**) the mixture after stirring.

3.3.1. Experimental Results

In this segment, we delve into the outcomes of the primary phase of the micro turbo-engine, emphasizing the initiation process. The startup phase is outlined as the interval from the initial activation of the starter to the juncture where the engine achieves a steady operational condition. The primary aim is to evaluate the consistency of the startup procedure across different fuel blends. Figures 5–7 illustrate the fluctuations in engine attributes throughout this phase, encompassing rpm versus time, fuel temperature versus rpm, and fuel flow rate versus rpm. These graphical representations provide insights into the dynamics and efficiency of the engine during the critical startup period for each fuel blend.

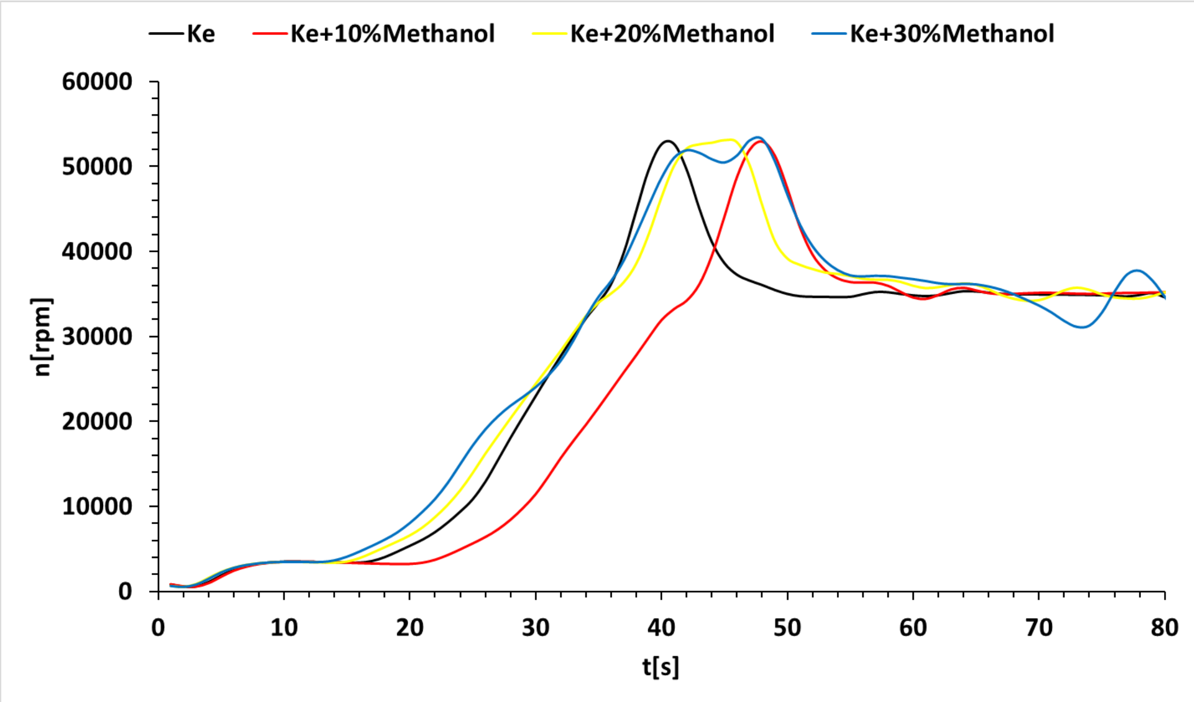

Figure 5. The rpm variation over time during the startup procedure until a stable output is attained.

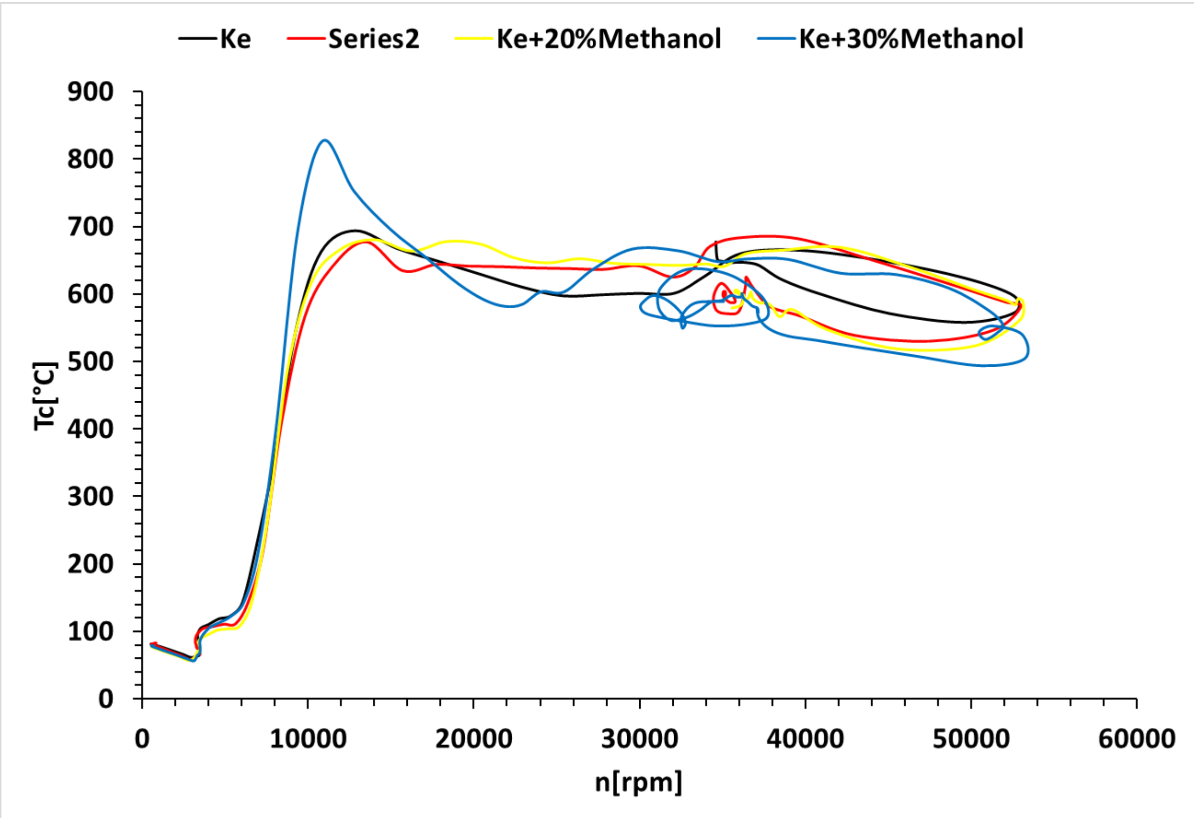

Figure 6. Temperature before the turbine (Tcomb) plotted against rpm for various fuel blends during the starting procedure.

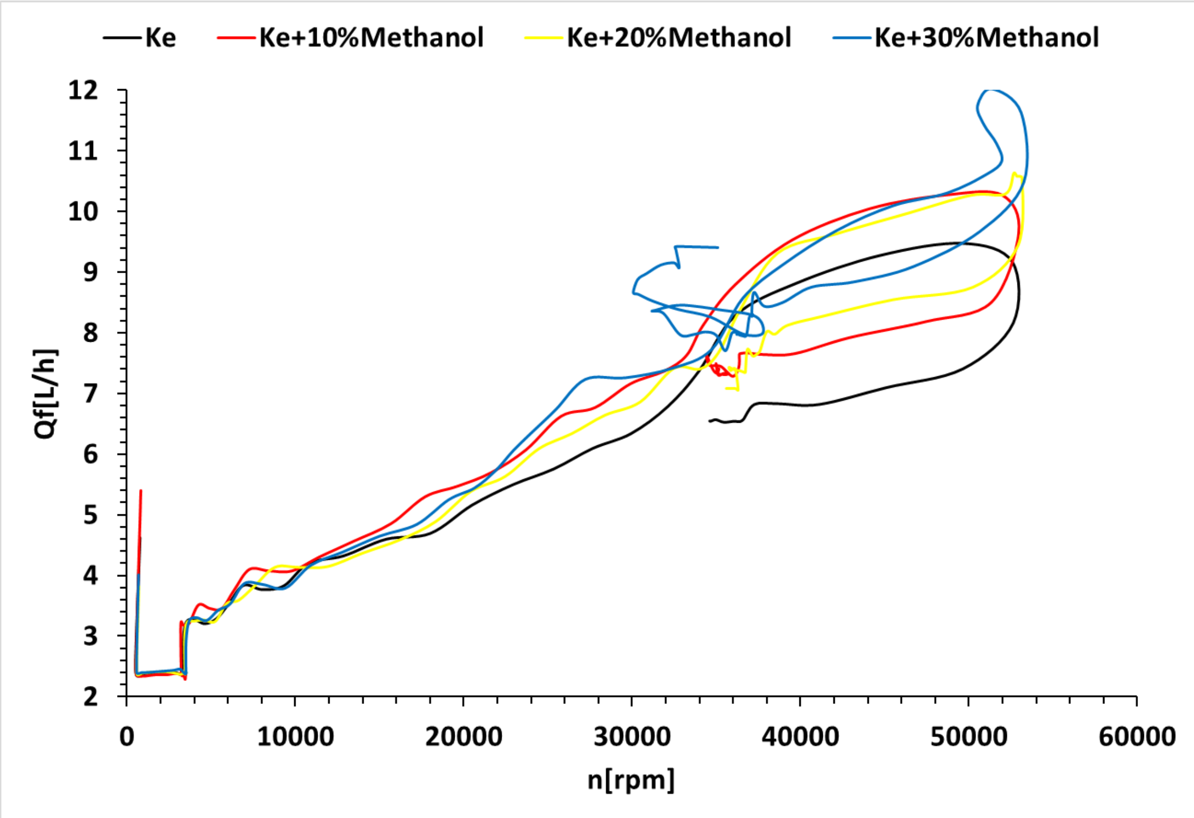

Figure 7. Q_c (L/h) vs. rpm for different fuel blends during the starting procedure.

Figure 5 shows that as the methanol concentration increases, the starting time increases too. For the first concentration of methanol (Ke+10%M), the starting procedure is relatively stable. As the concentration increases, at Ke+20%M, the starting time is lower but the maximum rpm was hard to maintain, as it can be seen in the summit of the yellow line. As the engine reached the yield regime, rpm is more oscillating than in the case of Ke. The starting procedure presents large difficulties in the case of 30% methanol, and maximum rpm cannot be held by the engine. After reaching yield regime, the rpm oscillations increased even more.

The fluctuations illustrated in Figure 6 suggest that following the initiation process, a minor decline in fuel temperature occurs. This phenomenon arises because, during the activation of the engine using the electric starter, external air is drawn into the combustion chamber.

Additionally, Figure 6 illustrates the ignition delay, which extends as the ethanol concentration rises. This delay leads to a decrease in temperature in front of the turbine during the starting procedure, consequently prolonging the entire starting process.

As for the fuel debit, it can be observed in Figure 7 that it increases while the methanol concentration increases throughout the entire starting procedure. Even more, for Ke+30%M, an anomaly compared to the engine's working law can be observed when the max rpm is attempting to be reached. This can also be assessed from Figure 6 where the combustion temperature for the blend containing Ke+30%M is very high and very instable during the entire starting procedure.

During yield regime, both fuel debit and combustion temperature for Ke+30%M show large oscillations, leading to the conclusion that blends consisting of more than Ke+20%M in aviation fuel is not a feasible solution for micro turbo-engines.

To evaluate the engine's combustion stability, a sudden procedure has been operated.

It involved a rapid transition from idle to maximum, followed by a stationary period of 30 s at the maximum, and then a sudden return to idle.

Figures 8–10 illustrate the fluctuations in temperature in front of the turbine, fuel flow, and thrust compared to rpm during this abrupt procedure for all four fuels under consideration.

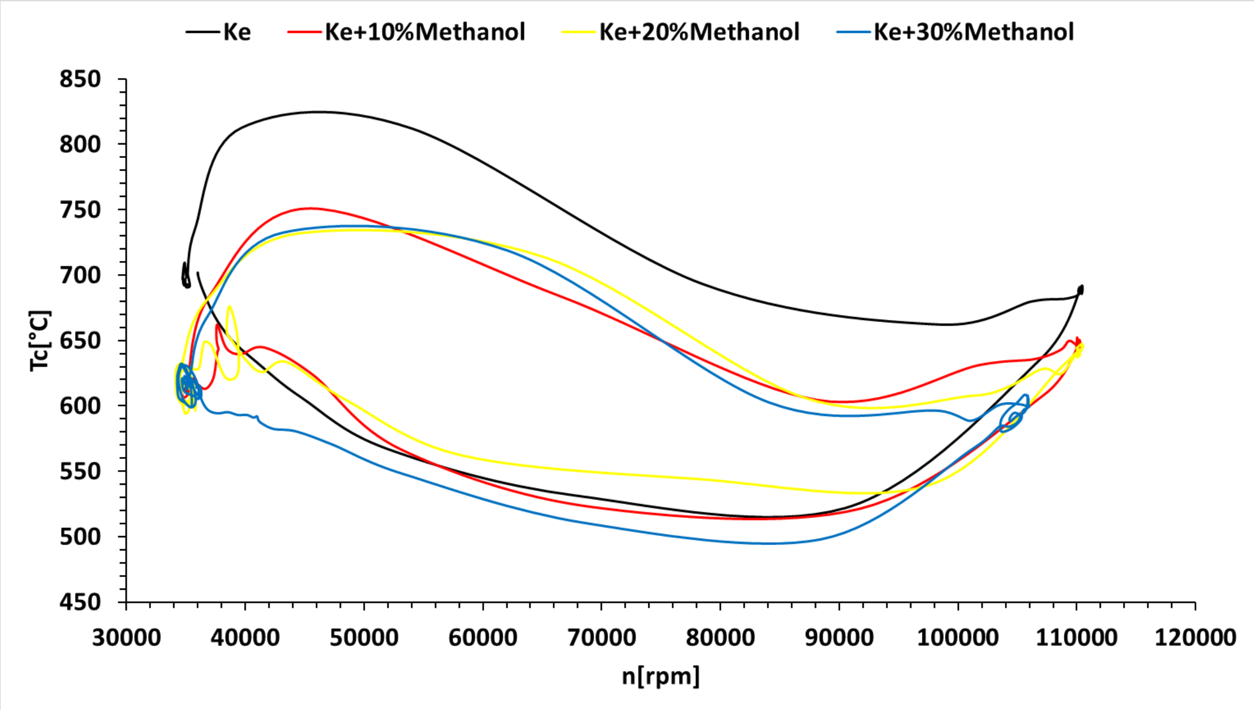

Figure 8. Temperature before the turbine (Tcomb) during rapid acceleration and deceleration.

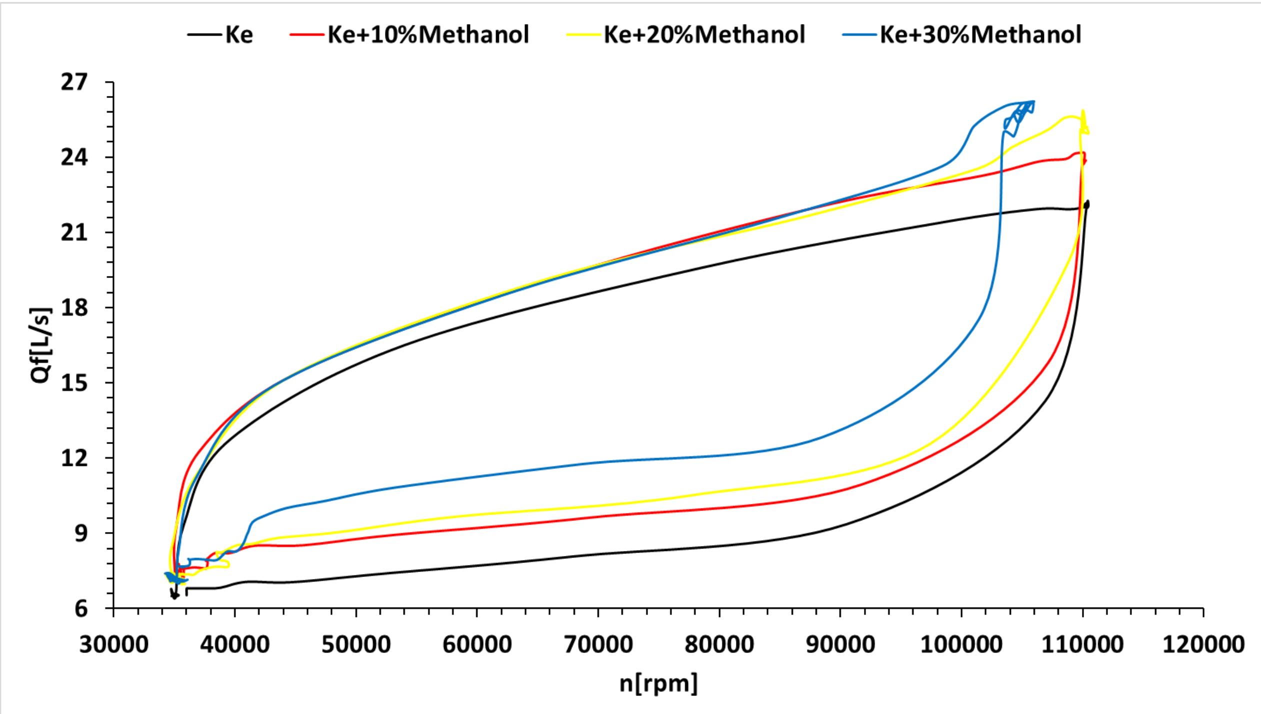

Figure 9. Variation in fuel flow during abrupt acceleration and deceleration.

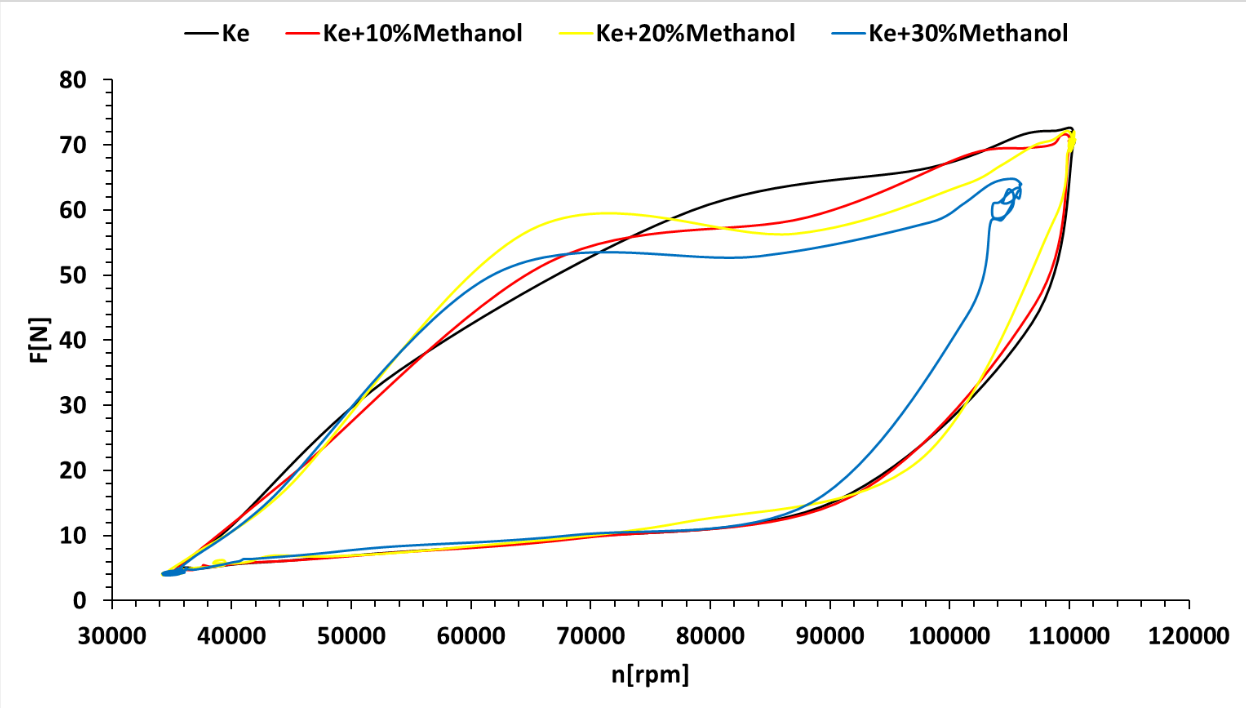

Figure 10. Thrust variation during rapid sudden acceleration and deceleration.

As depicted in the aforementioned figures, the engine underwent rapid acceleration, maintained maximum regime for a brief period, and then promptly decelerated, leading to a reduction in temperature ahead of the turbine during both acceleration and deceleration phases. Moreover, the temperature decreases as the alcohol concentration increases, although this does not pose a threat to the engine itself.

On the other hand, for the blend consisting Ke+30%M, during the sudden acceleration period, the stability of the burning process is disturbed, thus leading to the conclusion that at concentrations higher than 20%, the engine itself might be dangerously affected. The fuel flow exhibits an anticipated increase during the sudden acceleration sequence, which is expected. Interestingly, this trend persists with higher alcohol concentrations. This occurs because the calorific value of the blend decreases as the alcohol concentration increases. Also, the thrust shows similar behavior due to the same aspects of the blends.

The observations from the above figures indicate that as the concentration of methanol increases, the stability of the engine at idle and particularly at maximum speed decreases significantly. Specifically, at a concentration of 30% methanol, the engine no longer operates stably, exhibiting large fluctuations in rpm, leading to the decision not to experiment with higher concentrations. Ke+30%M is not a feasible solution for sudden acceleration/decelerations since the engine is unstable and may affect its integrity and leading to serious working problems.

Figure 11 visually presents the temperature fluctuations in front of the turbine across all three operating modes and various tested fuel combinations. Upon analyzing Figure 11, it can be deduced that the engine remained safe and intact since the turbine's maximum temperature of 800 °C was neither reached nor surpassed. Notably, in the idle mode, the temperature diminishes with an increase in alcohol concentration, attributed to the inherent instability of the idle regime. At higher regimes, combustion temperatures decrease significantly as the methanol concentration rises in the tested fuel blends. The temperature variation, correlated with other parameters, influences specific fuel consumption, combustion yield in the combustion chamber, and thermal yield.

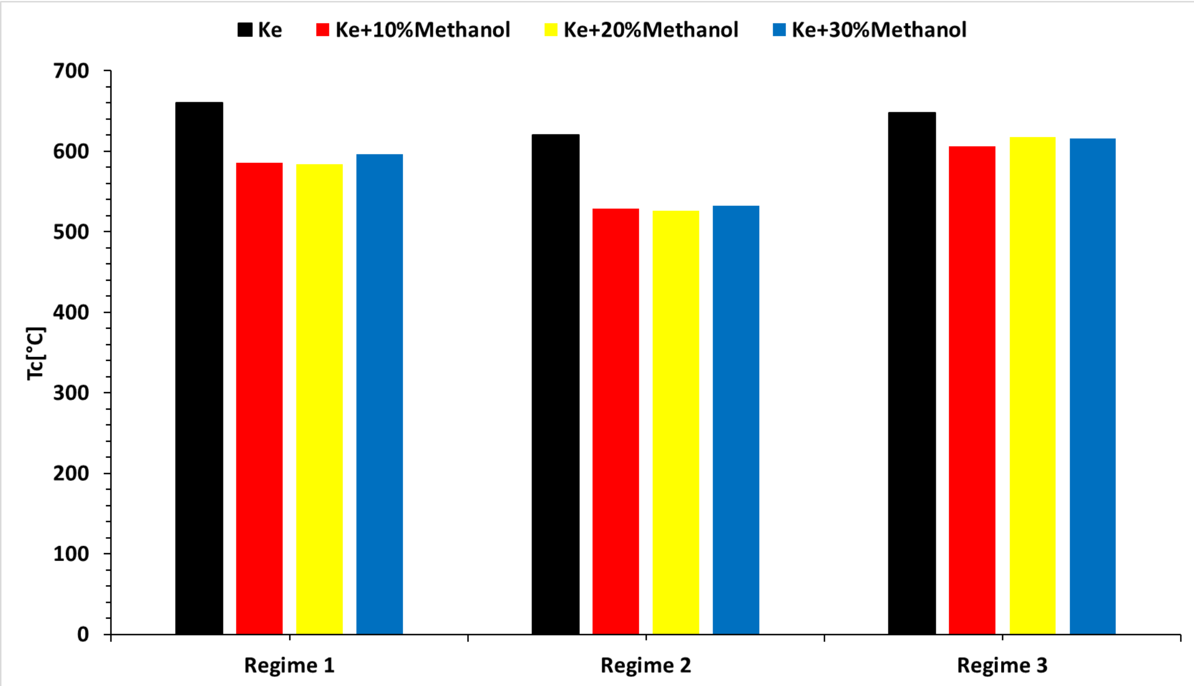

Figure 11. T_fuel vs. speed and blends.

Figure 12 illustrates the variation in consumed fuel flow in liters per hour, revealing a noteworthy increase across all three modes and tested fuel blends. Figure 13 depicts the thrust variation (F) based on the regime and tested blends. It is noticeable that thrust variations are minimal for regimes 1 and 2 but decrease during regime 3. Moreover, thrust diminishes with higher alcohol concentrations. The overarching conclusion drawn from these figures is that the engine's functionality and integrity were not compromised.

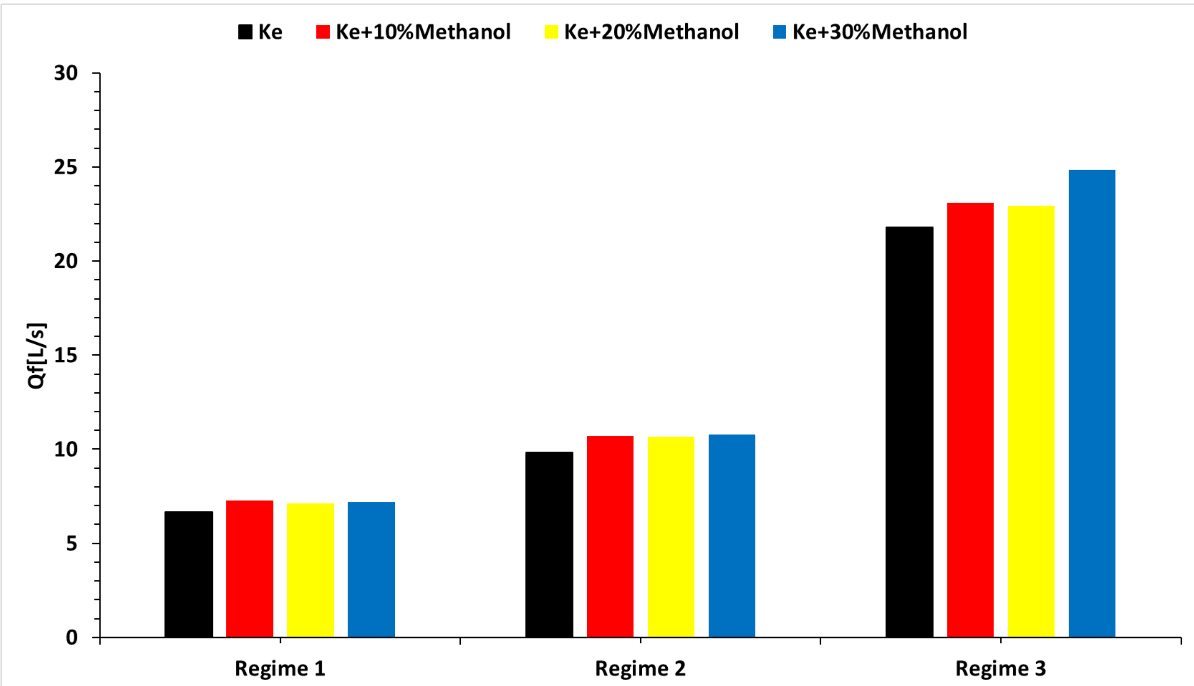

Figure 12. Qc vs. speed and blends.

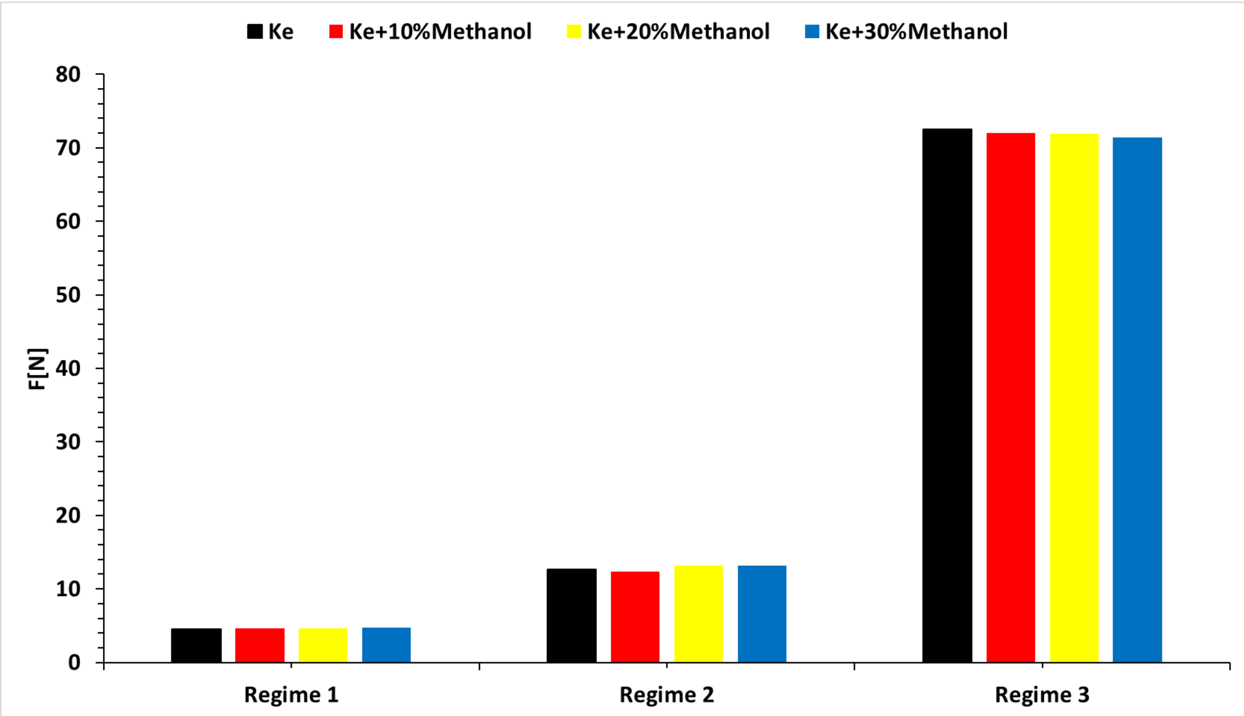

Figure 13. F vs. speed and blends.

Figures 14 and 15 are showing the variation in CO and SO_2 for all the blends used and for all three regimes.

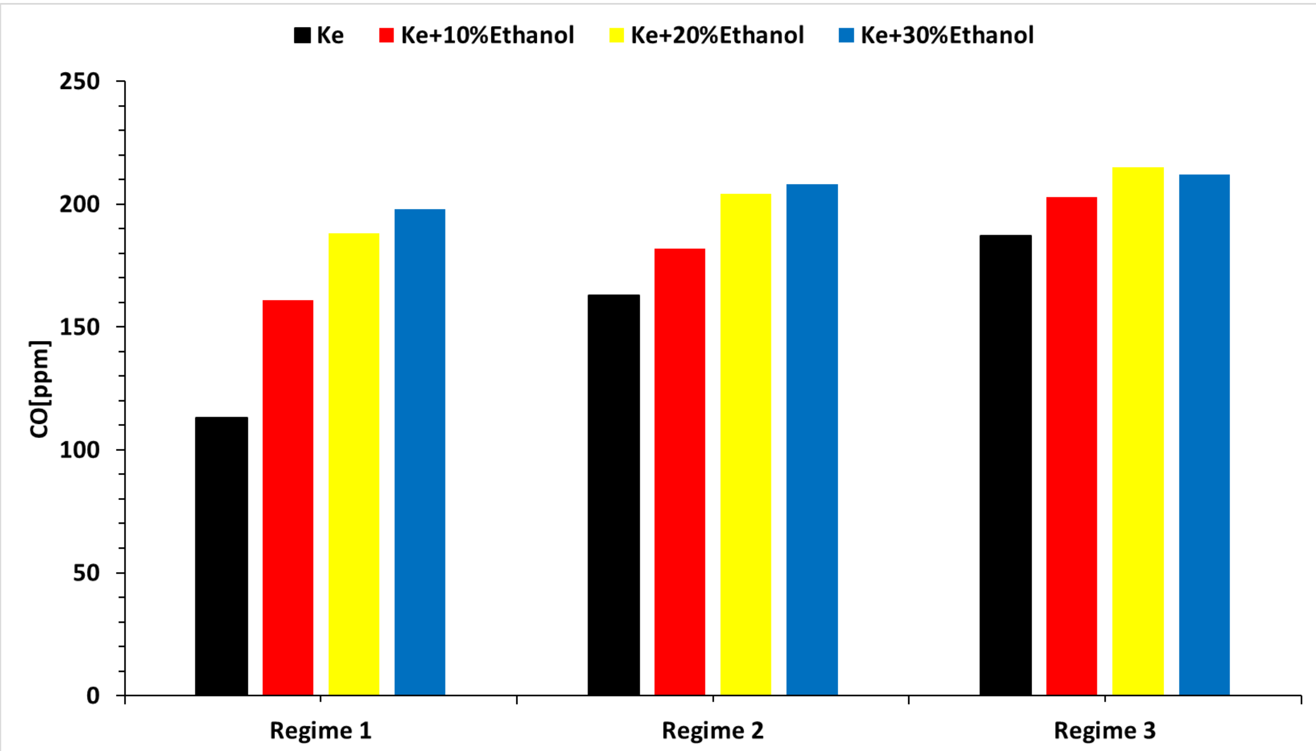

Figure 14. Concentration of CO versus operational modes and fuel blends.

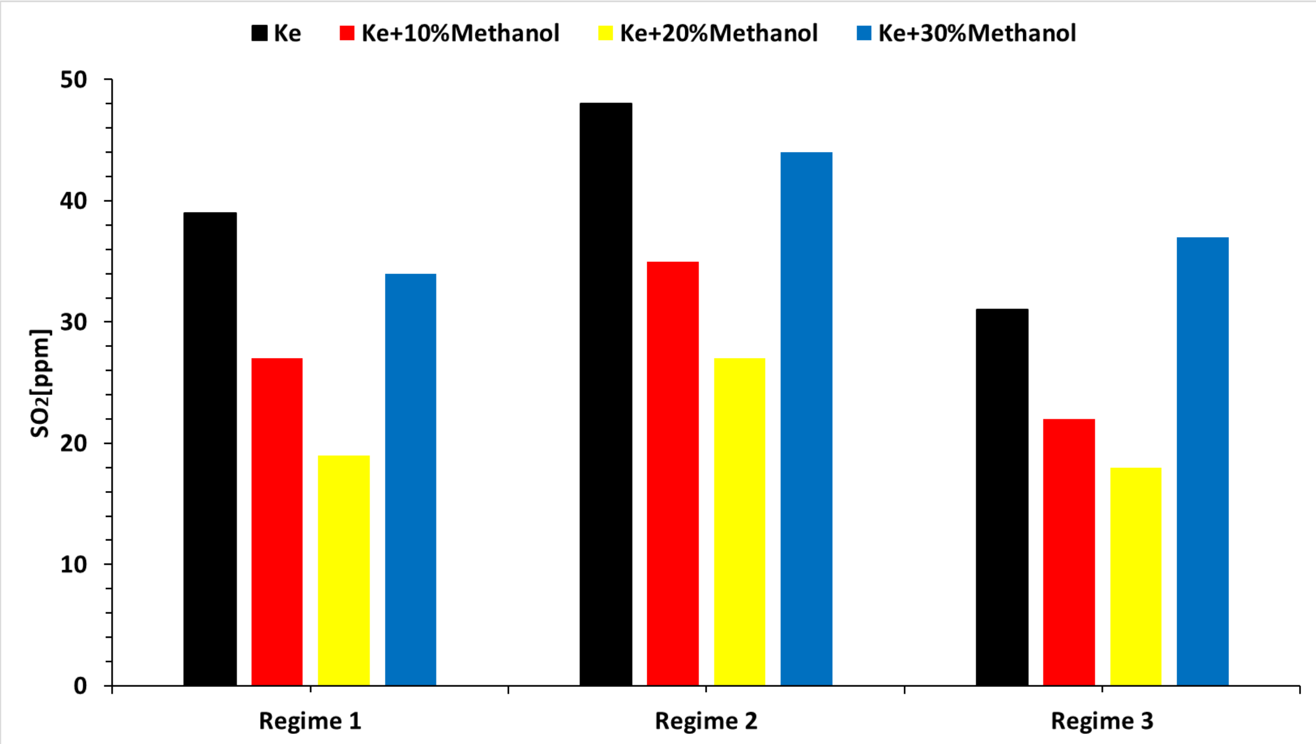

Figure 15. Concentration of SO_2 versus operational modes and fuel blends.

In Figure 14, as alcohol concentration increases, the concentration of CO rises. This occurs because alcohol in bringing into the blend more and more oxygen, which is actively participating in the burning reaction. Also, as the concentration increases, the required air for the stoichiometric reaction decreases, thus the burning is less efficient leading to the formation of CO. Also, CO formation is highly dependent on the temperature. Thus, a decrease in the temperature in front of the turbine is leading to an increase in CO formation rather than CO_2. As expected, CO concentration increases throughout the regimes since the fuel flow increases.

As for SO_2 formation, its variation does not depend on alcohol concentration. Indeed, as compared to Ke alone, adding alcohol into the blend decreases the SO_2 concentration. In terms of regimes, it seems that for Ke alone, max regime is the most efficient in terms of SO_2 production since the burning temperatures are the highest, but for the blends consisting of added alcohol, the idle regime seems to be the most efficient, maybe due to the oxygen brought into reaction by the alcohol.

3.3.2. Jet Engine Performance Analysis

Performance metrics are derived in accordance with the methodology specified in reference [31]. This involves ascertaining the density of every scrutinized fuel blend, facilitating the transformation of recorded fuel flow measurements from liters per hour to kilograms per second utilizing data from engine instrumentation. Subsequently, specific consumption (S) is computed utilizing Equation (5):

$$S = 3600 \cdot \frac{\dot{M}f}{F} \left[\frac{kg}{N \cdot h} \right] \quad (5)$$

where $\dot{M}f$ denotes the fuel flow in kilograms per second. Comprehending the progression of combustion inside the combustion chamber and assessing the degree of combustion completeness are crucial. Determining combustion efficiency (η_b) is critical in this context. It is represented by Equation (6), offering a quantitative assessment of the combustion process's effectiveness. This efficiency serves as a valuable indicator for assessing engine performance and combustion dynamics.

$$\eta_b = \frac{\left(\dot{M}f + \dot{M}a\right)cp_{3\_comb}\cdot T_{\_comb} - \dot{M}a\cdot cp_{\_comp}\cdot T_{\_comp}}{\dot{M}f\cdot LCV} \quad (6)$$

where LCV—lower calorific value, cp—specific heat capacity, and T_{comb} represents the temperature in front of the combustion chamber that was recorded.

The thermal efficiency of an engine, an essential metric for performance evaluation, is calculated as the ratio between the net rate of useful work output and the rate of thermal energy available from the fuel consumed by the engine.

Equation (7) encapsulates this parameter, offering a quantitative gauge of the engine's efficiency in converting thermal energy from fuel combustion into useful work output. It stands as a pivotal metric for evaluating the overall performance and energy conversion efficiency of the engine under investigation.

$$\eta_T = \frac{\left(\dot{M}a + \dot{M}f\right)\cdot v_e^2}{2\cdot \dot{M}f\cdot LCV} = \frac{\left(\dot{M}a + \dot{M}f\right)\cdot \left(\frac{F}{\dot{M}a+\dot{M}f}\right)^2}{2\cdot \dot{M}f\cdot LCV} \quad (7)$$

Figure 16 displays the variation in specific consumption across all the examined fuel blends.

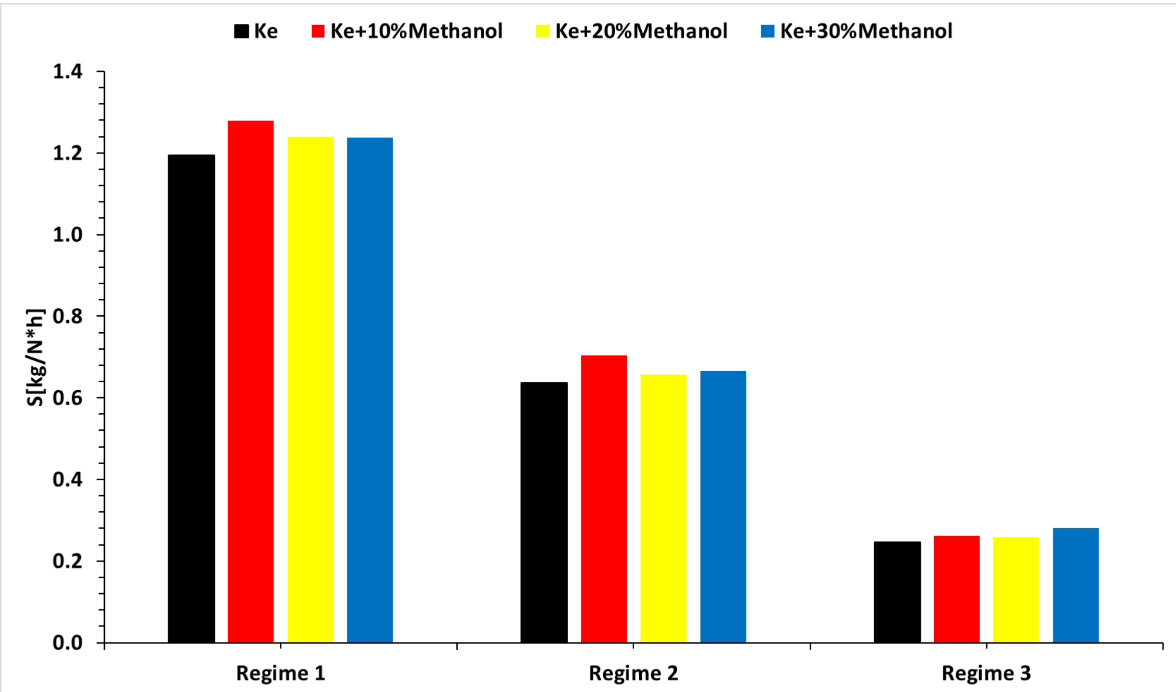

Figure 16. Variation in the fluctuations in specific consumption among all the tested fuel blends. The specific consumption of the turbo-engine indicates an increase, as anticipated, owing to the lower calorific value of methanol compared to that of Jet-A. The reduced calorific value and the fuel blends exhibit higher specific consumption, in comparison to Jet-A, indicating that the inclusion of methanol in aviation fuel would require larger fuel tank capacities to accommodate the greater fuel consumption associated with methanol utilization.

This observation underscores the potential implications for aircraft design and fuel storage considerations in the context of introducing methanol as an aviation fuel.

Figure 17 illustrates the combustion efficiency as a function of operating regime and methanol concentration in the fuel blends.

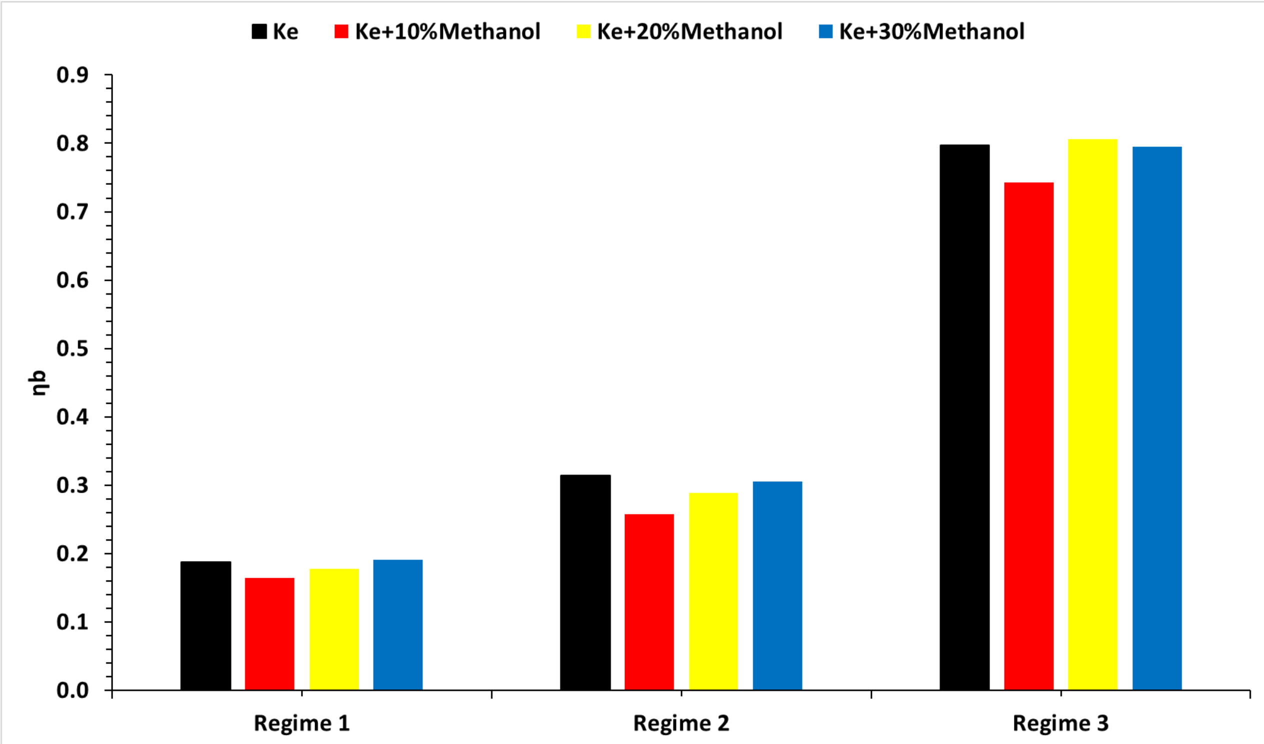

Figure 17. The combustion efficiency vs. regimes and blends.

The burning efficiency is lower in the case of the blends compared to that of Ke alone and decreases as the alcohol concentration increases for all three regimes.

The thermal efficiency values computed using Equation (7) are presented in Table 3. It should be noted that thermal efficiency was determined solely for the maximum operating regime.

Table 3. Calculated thermal efficiency obtained at maximum regime for all tested blends.

Fuel	Ke+5%Aeroshell 500 Oil	Ke+10%M	Ke+20%SM	Ke+30%M
η_b [%]	5.197	5.149	5.524	5.346

η_b Upon analyzing Table 3, it becomes evident that the thermal efficiency values are notably low in comparison to those reported in the literature. This discrepancy is attributed to the distinct operating procedures of the turbo-engine under consideration, which differ from those employed in traditional airplane turbo-engines. Notably, the thermal efficiency is lower for the fuel blends than for Ke (kerosene) alone, and it demonstrates an increase with higher alcohol concentrations in the blends. This observation underscores the influence of fuel composition on the thermal efficiency of the turbo-engine, emphasizing the need for specific considerations and adjustments when assessing efficiency in non-standard engine configurations.

4. Conclusions

- Experimental assessments conducted on the Jet CAT P80®micro turbo-engine demonstrate that the inclusion of methanol in conventional fuel does not jeopardize the performance of the turbo-engines. The calorific value of the fuel blends experiences a decrease with increasing methanol concentration, resulting in a corresponding rise in specific fuel consumption. The lower percentage of carbon content in methanol, used for blending with Ke (kerosene), contributes to reduced CO_2 emissions upon combustion.

- Concerning engine performance, there is a proportional increase in fuel-specific consumption with higher methanol percentages in the tested blends, a trend attributed to their respective calorific values.
- The concentrations of CO and SO_2 vary primarily with operational regimes and secondarily with alcohol concentrations. However, further investigations are warranted to explore the formation of additional gaseous pollutants such as NOx, volatile organic compounds (VOC), and CO_2.
- The key finding is that the tested fuel blends, namely, Ke+10%M, Ke+20%M, and Ke+30%M, are deemed suitable for aviation applications utilizing micro turbo-engines. Throughout the experiments, the integrity of the engine remained intact, affirming their viability for practical aviation use.

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