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# The Use of Ethanol as an Alternative Fuel for Small Turbojet Engines

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**Abstract:** The use of alternative fuels to traditional kerosene-based ones in turbo-jet engines is currently being widely explored and researched. However, the application of alternative fuels in the area of small turbojet engines with thrust ratings up to 2 kilo-newtons, which are used as auxiliary power units or to propel small aircraft or drones, is not as well researched. This paper explores the use of ethanol as a sustainable fuel and its effects on the operation of a small turbojet engine under laboratory conditions. Several concentrations of ethanol and JET A-1 mixtures are explored to study the effects of this fuel on the basic parameters of a small turbojet engine. The influence of the different concentrations of the mixture on the start-up process, speed of the engine, exhaust gas temperature, and compressor pressure are evaluated. The measurements shown in the article represent a pilot study, the results of which show that ethanol can be reliably used as an alternative fuel only when its concentration in a mixture with traditional fuel is lower than 40%, yielding positive effects on the operating temperatures and small negative effects on the speed or thrust of the engine.

**Keywords:** ethanol; alternative fuel; small turbojet engine; turbojet engines



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## 1. Introduction

In 2017, greenhouse gas (GHG) emissions from the transportation sector (including international aviation) in the EU-28 represented 25% of the total, whereas in 1990, they represented only 15% [1]. Aircraft produce around 2% to 3% of the carbon dioxide ($CO_2$) emissions worldwide [2]. This value will probably grow or stagnate after the corona crisis is over, as the number of passenger and cargo transport aircraft was expected to increase to 48,000 by 2038 [3].

Traditional aviation fuels are produced by the distillation of crude oil. There are also some alternative fuels potentially suitable for aviation, including methanol, ethanol, butanol, liquid natural gas, liquid hydrogen, and synthetic fuels made from coal, natural gas, or other hydrocarbon (HC) feedstock [4]. Presently, much research is currently focused on aviation biofuels.

Alternative alcohol-based fuels were first proposed in 1907 for possible use in the automotive industry [5]. Today, the most common alcohol-based fuel for piston combustion engines in automobiles is ethanol [6–8]. This fuel is used in advanced countries as an additive to normal petrol fuels, usually at a concentration of 10% (E10) but also at 20% (E20), 85% (E85), and even 100% (E100) [9–11]. Using such a concentration demands thorough testing of these engines. The small content of ethanol in fuel does not significantly affect the mechanical and energy characteristics of an engine [12]. However, it increases thermal efficiency and improves the anti-detonation properties of the fuel [5]. $CO_2$ and unburned HC emissions increase with ethanol content in the fuel [13], which produces lower tailpipe emissions in terms of total HCs and carbon monoxide (CO); however, ethanol also causes a significant increase in the emissions of acetaldehyde [13]. E10 was observed to cause higher emissions of nitrogen oxide ($NO_x$) than E0 [14]. The use of E20 fuel had an impact on decreasing damage to human health by 1.3% and decreasing damage to the ecosystem by 1.4% and natural resources by 12.9% [13].

The influence of ethanol was also tested in diesel engines, where a significant decrease in performance was observed using a mixture of diesel and ethanol. On the other hand, the smoke values and $NO_x$ values were reduced [15]. Mixing ethanol and aviation JET A fuel was done in a four-stroke direct injection diesel engine, thereby obtaining higher efficiency and ecological benefits [16].

The influence of biofuels and alcohol-based mixtures on gas turbines has also been tested in power engineering. More ethanol content caused greater CO emissions. $NO_x$ was reduced for biofuels by up to 70%, and particulate matter (PM) was also reduced [17].

The first tests and certifications of ethanol and aviation fuel mixtures were performed on piston engines with carburettors. It was found that an aviation piston engine can operate with any mixture of aviation gas (AVGAS) and ethanol [18]. However, a recent review emphasised the advantages of the fuel properties of butanol over methanol and ethanol for use in internal combustion engines [19,20].

Testing and comparison of clean JET A fuel with ethanol was also performed on aviation gas turbine engines, where it was found that the engine had a slower dynamic response when using ethanol in the fuel mixture. This was remedied by a redesign of the controller gains [21].

Other tests were aimed at mixtures of butanol and JET A fuel. The results showed that butanol has several advantages over ethanol, including higher energy content, lower vapour pressure, lower water absorptivity, and fewer corrosive effects. The results show that the performance parameters such as thrust and exhaust gas temperature (EGT) for Jet A-1/butane blend are comparable to or smaller than those for pure JET A-1. The fuel consumption and specific fuel consumption were slightly higher, up to 5% for full thrust and 2% for normal operation, for the blend with butanol than for JET A-1. On the other hand, the values of CO, $CO_2$, and $NO_x$ concentrations for the JET A-1/butanol blend were slightly lower—3%, 2%, and 2%, respectively—than those of JET A-1 [22,23].

The use of biofuels has also considerably increased in recent years. Different generations of biofuels, methods of production, and ecological and economic benefits have been thoroughly researched [3,4,24]. Bio-jet fuels have good thermal stability, excellent combustion properties, and good low-temperature fluidity but relatively poor oxidative stability and are not compatible with current fuelling systems due to a swell of the sealing materials and lubricity [25]. Alternative aviation fuels have lower energy content per unit weight and volume than traditional fuels. The specific energy of pure ethanol is 58% and its energy density is 60% compared to JET A-1.

Small turbojet engines can provide a good testing platform for alternative fuels and various fuel blends. A test of JET fuel using a small turbojet engine with synthesised paraffinic kerosene (SPK) from hydro-processed esters and fatty acids (HEFA) showed a decrease in fuel consumption, as well as a decrease in CO, HC, PM, and $NO_x$ emissions [24].

Test of blends containing Jet A-1 and 10–50% d-limonene, 10–25% butyl butyrate, 25% n-butanol, and 25% ethanol were also used on small turbojet engines. Each tested blend resulted in minimal performance changes at most operating throttle settings [26].

In a test of 2-Ethylhexanol (2-EH) and Jet A-1 fuel, it was found that the thrust, fuel consumption, and CO emissions between the tested fuels were negligible, not exceeding 3%. In case of $NO_x$ emissions, higher values were obtained for the 2-EH fuel than for clean Jet A-1 [27]. A 20% palm oil biodiesel fatty acid methyl ester (PME) blend with JET A-1 was also tested, where slight performance penalties were observed due to the lower energy content of the biodiesel blend [28]. A small-scale gas turbine engine with a power output of 30 kW fuelled with JET A-1/ethanol blends was also researched using concentrations from 25% to 100% for the ethanol mixture in the fuel/ethanol blend [29]. Researchers found that the CO and $NO_x$ emissions were comparable between the blended and clean JET A-1 fuel, and the $NO_x$ emissions were lower for the mixture of JET A-1/ethanol because of the lower temperature at the turbine inlet [29,30].

Based on these different and sometimes controversial effects of burning alcohol and JET A-1 mixtures with similar combustion characteristics, but with much lower soothing propensity than pure kerosene, ethanol was selected for the experiments to apply it as an alternative fuel in small-scale turbojet engines, which is an area that remains poorly explored. The aim of this study is to summarise and explore the effects of using ethanol in a small-scale turbojet engine and to explore whether a mixture of JET A-1 and ethanol is a viable fuel for use in small turbojet engines, as indicated by previous studies. The other aim is to explore the concentrations that are viable to be used for small turbojet engine, as well as the effects of alcohol-based fuel on the operational parameters of jet engines. The results could help broaden the knowledgebase for using alternative fuels in small turbojet engines, and some knowledge from the described experiment can also be used to supplement knowledge about the use of alternative fuels in large turbojet engines or gas turbine engines in general.

## 2. Materials and Methods

To evaluate the hypothesis of the application and effects of different JET A-1/ethanol fuel blends on a small turbojet engine, we used an engine test stand with a digital data acquisition system in a laboratory. The engine used in the experiments is a small turbojet engine, MPM-20, with a radial compressor and a hydromechanical control unit. This is a small turbojet engine with a thrust of up to 500 Newtons, an annular combustion chamber, and a radial single sided compressor. The engine is a one-shaft engine with direct air flow and a single disc uncooled turbine featuring a fixed exhaust nozzle [31,32]. This is a simple and traditional turbojet engine construction; thus, it is expected that the results of the tests will be valid for similar class of engines, as well as for engines with small power outputs and airflows. The engine and its installation are shown in Figure 1.

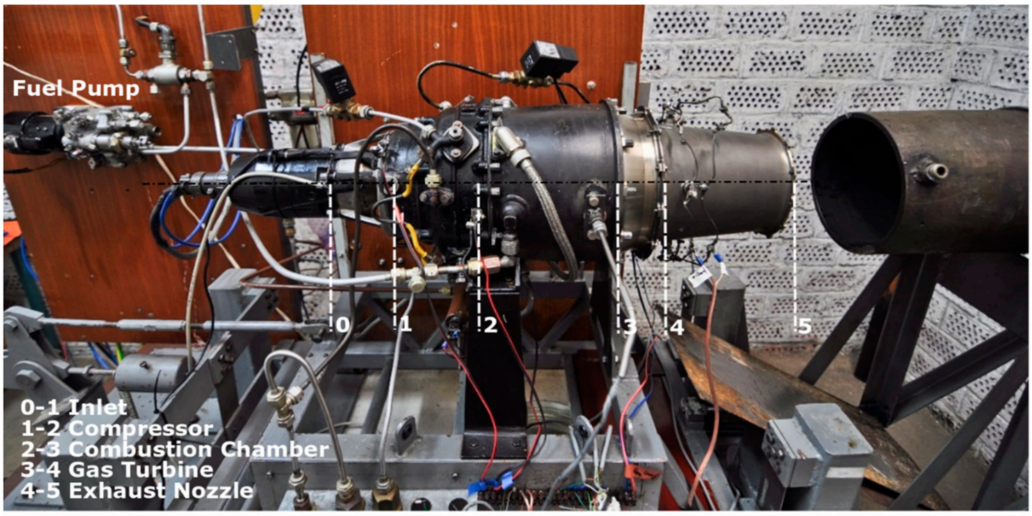


**Figure 1.** MPM-20 Engine, test bench installation.

The alternative fuel in our experiment is a blend of JET A-1 fuel and ethanol. Ethanol is a colourless flammable liquid that can be easily produced from different renewable sources. Ethanol is also less toxic than other alcohol-based fuels. Its main deficiency is its water binding properties, which can cause corrosion in engines. This shortcoming can be remedied via additives [33,34]. The basic chemical properties of pure ethanol (less than 0.1% of water) are listed in Table 1.

**Table 1.** Basic chemical properties of ethanol [35,36].

| Systematic Name | Ethanol—Hydroxyethane |
|---|---|
| Rational name | Ethanol (99.9%) |
| CAS Registry No. | 64-17-5 |
| Summary formula | $C_2H_6O$ |
| Molecular weight | 46.07 g/mol |
| Melting point | −114.4 °C |
| Freezing temperature | −130.5 °C |
| Boiling point | 78.3 °C (1013 hPa) |
| Density (at 20 °C) | 0.789 g/cm$^3$ |
| Flash point | 12.7 °C (<0.1% of water)<br>13.57 °C (10% of water)<br>19.33 °C (50% water) |
| Burning temperature | 30 °C |
| Ignition temperature | 366 °C |
| Explosion limits | 3.4–15% of volume |
| Kinematic viscosity | 1.5 mm$^2$/s (at 20 °C, 1 atm) |
| Dynamic viscosity | 1.184 mPa·s (at 20 °C, 1 atm) |
| Specific heat | 2 460 J/(kg·K) |
| Higher heating value | 29.7 MJ/kg |

### 2.1. The Experimental Engine and Measurement System

A small turbojet engine, MPM-20, was used as a test engine to evaluate the effects of using ethanol and JET A-1 fuel blends. In the tests, this engine was only partly digitally controlled with a real-time data acquisition system [37]. To test the effects of alcohol-based fuels, a hydro-mechanical fuel pump with a partial digital control was used so the parameters of fuel flow (FF) would not be optimised, and the fuel flow could be constant and start-up fuel flows could have the same curve in each experiment without specific optimisations of a fully digital control system.

The parameters and sensors that were used to measure them are shown in Table 2. They were dynamically measured with a constant sampling frequency of 10 Hertz. The scheme of the data acquisition system and the arrangement of the sensors from Table 2 are shown in Figure 2. This figure shows precisely the placement of each sensor on the engine using the engine's 3D model. The figure also shows connection of the sensors through a bus into NI CDAQ 9717 data acquisition system.

**Table 2.** Sensors used in experiments.

| Parameter—Abbreviation | Sensor | Unit | Basic Calibrated Error |
|---|---|---|---|
| Fuel Flow—FF | Badger-meter MN-2 flow meter | (l.min$^{-1}$) | ±1% |
| Rotational speed of the engine—n | Optical speed meter | (min$^{-1}$) | ±0.2% |
| Total exhaust gas temperature—EGT | Calibrated K thermocouple | (°C) | ±0.75% |
| Total compressor pressure—p2 | QBE2002-P10 | (atm) | ±0.4% |

To sample and digitise data, we used a calibrated National instruments data acquisition system NI CDAQ 9172 with the following installed modules for real-time data acquisition:

- NI 9263—100 kHz Voltage Output Module, used for the control of analogue engine systems;
- NI 9472—8-Channel, Digital I/O Module, used for the control of digital engine systems;
- NI 9205—±10 V, 250 kHz, 16-Bit, 32-Channel C Series Voltage Input Module, used for the measurement of analogue sensors, in this case, QBE2002-P10;

- NI 9423—8 Channel Sinking Input, C Series Digital Module, used for the measurement of frequency signals, in this case, optical speed sensor;
- NI 9213—NI-9213, 16-channel, Thermocouple Input Module, used for the measurement of thermocouples, in this case, K-thermocouple EGT sensors.

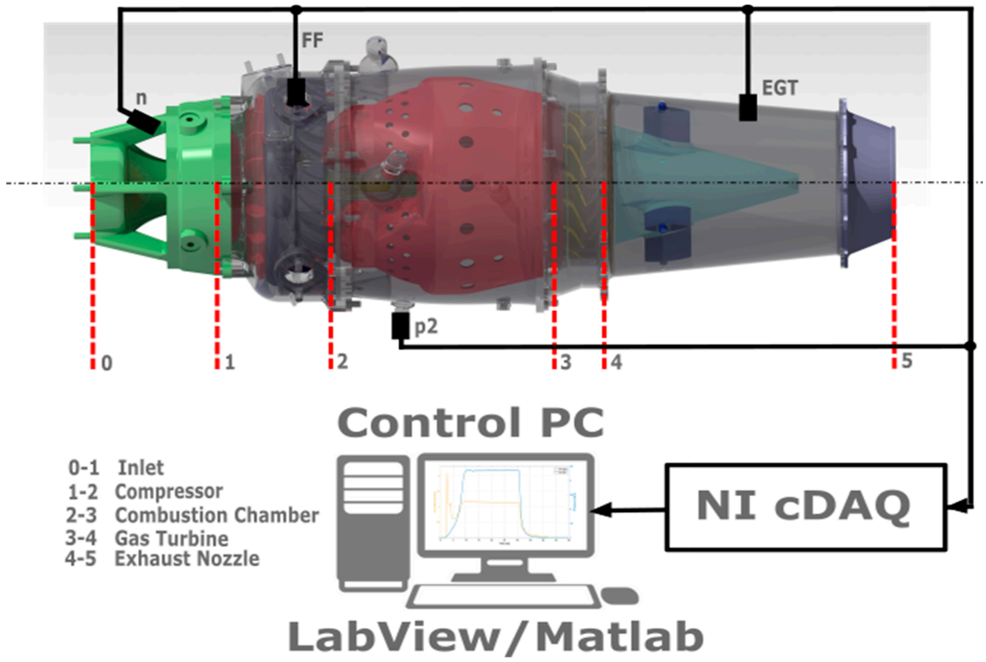


**Figure 2.** Scheme of the measurement system and placement of sensors.

Figures 3 and 4 show how the engine dynamically operates during a single run using clean JET A-1 fuel with a depiction of its basic parameters, which are evaluated for the effects of alternative fuels. As shown in Figure 3, the engine was run for approximately 25 s. Figure 3 shows the course of the engine speed and the Exhaust Gas Temperature (EGT), while Figure 4 shows the total compressor pressure and the fuel flow during standard operations of the engine at 46,000 min$^{-1}$. The EGT temperature reaches a peak of 800 °C. This is an important parameter, present in many turbojet engines, that needs to be analysed when using ethanol fuel blends or alternative fuels in general.

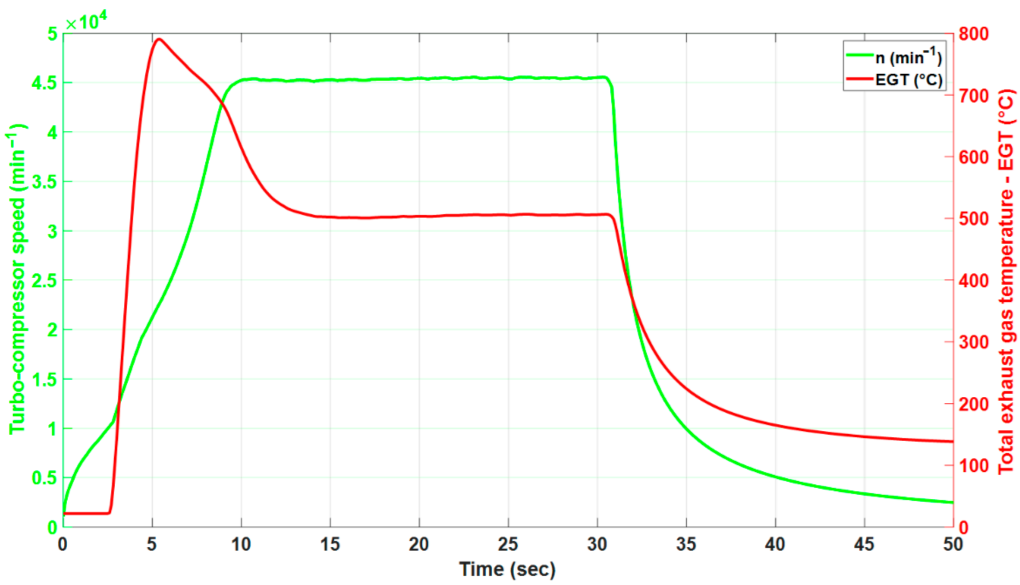


**Figure 3.** Exhaust gas temperature and speed of the engine during a single engine run.

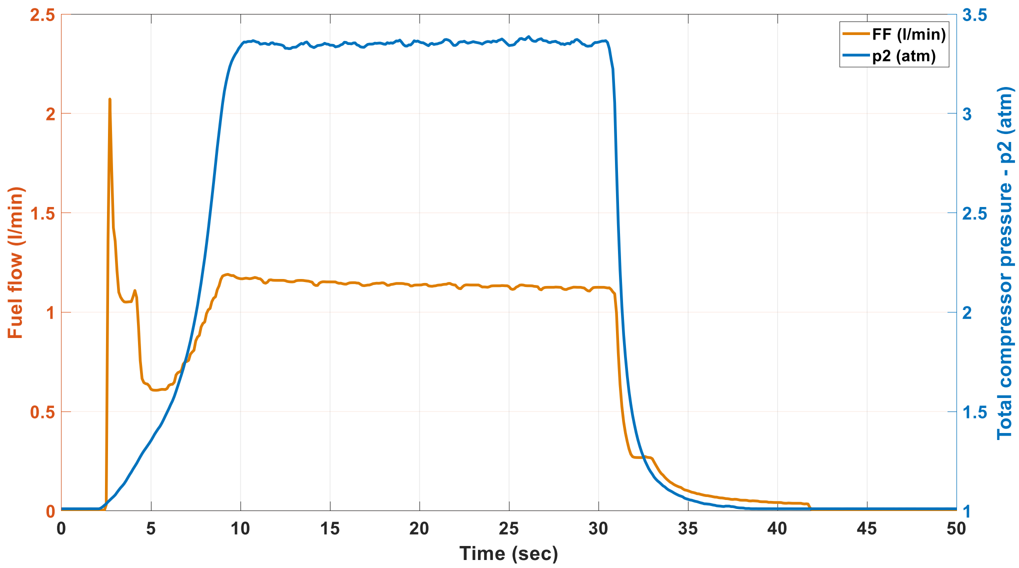


**Figure 4.** Fuel flow and compressor pressure during a single engine run.

Figures 3 and 4 also illustrate the three phases of operation of the engine—the start-up phase, the stable operation phase, and the shutdown phase—for which the engine's parameters were evaluated. The engine's hydromechanical fuel/oil pump was run at a constant speed, thus producing a constant fuel flow to secure the stable operation of the engine. Start-up of the engine was controlled hydromechanically based on compressor pressure in the feedback to control the fuel flow during start-up producing the same fuel flow curve in each run.

## 2.2. The Experimental Fuel

To evaluate the effects of ethanol and clean JET A-1 (E0) fuel blends on the operation of a small turbojet engine, concentrations of 10% (E10), 20% (E20), 30% (E30), and 40% (E40) ethanol in the JET fuel were analysed by the certified research facility, The Centre Of Metrology and Testing in Žilina. The results for the individual blends are presented in Table 3. Tests for density were done according to STN EN ISO 12185 [38], tests for viscosity were done according to STN EN ISO 3104+AC [39], and distillation tests were done according to STN EN ISO 3405 [40].

**Table 3.** Basic chemical properties of the studied JET A-1/Ethanol fuel blends.

| Test \ Concentration | | Units | E0 | E10 | E20 | E30 | E40 |
|---|---|---|---|---|---|---|---|
| **Density (at 15 °C)** | | (kg/m$^3$) | 814.1 | 810.6 | 808.2 | 805.8 | 803.6 |
| **Viscosity (at 20 °C)** | | (mm$^2$/s) | 2.052 | 1.885 | 1.863 | 1.820 | 1.774 |
| **Flashpoint in a closed container** | | (°C) | 61 | <16 | <16 | <16 | <16 |
| **Water reaction** | **PR *** | Degree | 1 | 1 | 1 | 1 | 1 |
| | **PL **** | | 2 | 3 | 3 | 3 | 3 |
| **Crystallisation** | | (°C) | −56.3 | <−105 | <−105 | <−105 | <−105 |
| **Acidity** | | (mg KOH/100 mL) | 0.17 | 0.15 | 0.14 | 0.12 | 0.08 |

* Phase range (PR); ** Phase level (PL).

The results presented in Table 3 show that the inclusion of even 10% ethanol in the fuel blend yields a distinct decrease in the flashpoint because ethanol is highly flammable. Ethanol is also highly hygroscopic, resulting in a very low point of crystallisation below −105 °C, as ethanol will bind all available water in the JET A-1 fuel. Viscosity also decreased; this means that some additives will be needed to improve this factor.

### 2.3. Calculation of the Gross Heat of the Combustion of Alternative Fuel Blends

Combustion is defined as an exothermic reaction in which a compound reacts completely with an oxidant. In the ideal complete combustion of organic compounds reacting with oxygen, every carbon atom in the original compound ends up in the $CO_2$, every hydrogen atom ends up in the $H_2O$, and every nitrogen compound ends up in $N_2$. However, in practice, combustion is usually not complete. The water produced in a combustion process ends up as a vapour or liquid, and the enthalpy of combustion is larger when the produced water is in a liquid state, rather than in a gas state.

The gross heat of combustion (or the higher heating value (HHV)) for a fuel is defined as the amount of heat released by a specified quantity (initially at 25 °C) once the fuel is combusted and the products have returned to a temperature of 25 °C [41]. The HHV includes the latent heat of condensation of the water, which is in a liquid state under these conditions. The HHV can be measured by a calorimetric bomb. The exact procedure is specified by the standard EN ISO 1716:2018 [42]. As the combustion of any substance is an exothermic reaction, the HHV will be a positive value.

The gross heat of combustion can be determined by Equation (1):

$$Q_{PCS} = \frac{E(T_m - T_i + c) - b}{m} \tag{1}$$

where

$Q_{\mathrm{PCS}}$ is the gross heat of combustion (MJ/kg);
$E$ is the water equivalent of the calorimeter, the bomb, accessories, and the water introduced into the bomb (MJ/kg);
$T_{\mathrm{i}}$ is the initial temperature (K);
$T_{\mathrm{m}}$ is the maximum temperature (K);
$b$ is the correction required for the combustion heat of the "fuels" used during the test, i.e., the firing wire, cotton thread, cigarette-making paper, and benzoic acid or combustion aid (MJ/kg);
$c$ is the temperature correction factor required for the exchange of heat with the outside, which is nil if an adiabatic jacket is used (K);
$m$ is the mass of the test specimen in kilograms (kg).

The $Q_{\mathrm{PCS}}$ of the tested fuel blends of JET A-1 and ethanol, under various concentrations, were determined according to the standard EN ISO 1716:2018 [42] and are presented in Table 4 and depicted in Figure 5.

**Table 4.** The gross heat of combustion for blends of JET A-1 with ethanol.

| Ethanol Percentage in JET A-1 (%) | HHV (MJ/dm$^3$) | HHV (MJ/kg) |
|---|---|---|
| 0 | 37.61 | 46.2 |
| 10 | 36.26 | 44.55 |
| 20 | 34.92 | 42.9 |
| 30 | 33.58 | 41.25 |
| 35 | 32.9 | 40.42 |
| 40 | 32.23 | 39.6 |

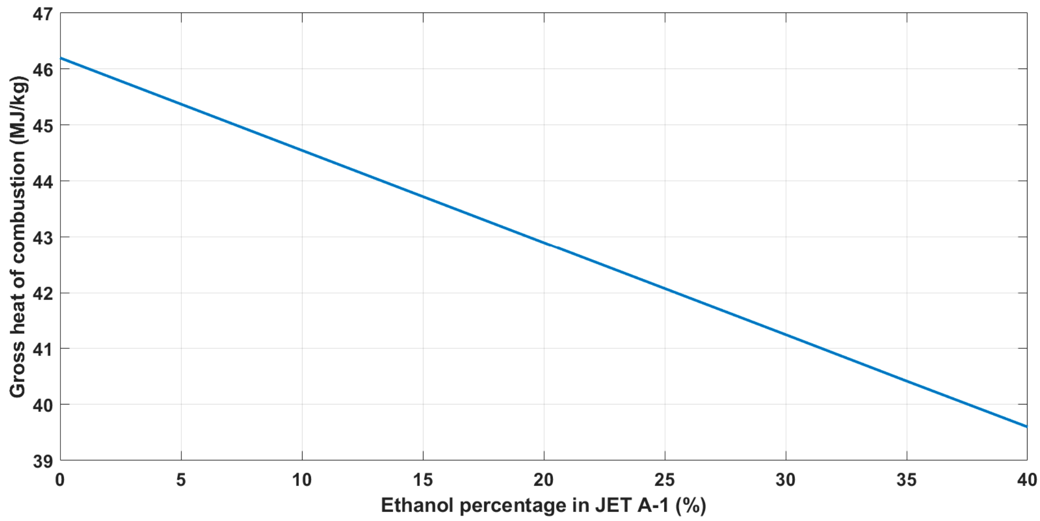


**Figure 5.** Gross heat of combustion for different ethanol concentrations in JET A-1.

### *2.4. Experimental Design*

According to the computed gross heat of combustion and the defined hypothesis in the introduction of this paper, the experimental design was created as follows. We initially proposed to test concentrations with fuel blends designated as E0, E10, E20, E30, and E40. Since preliminary tests showed that an E40 blend will be problematic for the engine during start-up, the E35 blend was added to the experiment. All blends were mixed using a certified facility for creating fuel blends. The clean fuel was compliant with the standards of SN_0501_01/ASTM D 1665/AFQRJOS 23 [43]. Moreover, the ethanol used in experiments was compliant with the conditions set in the test for waterless ethanol of 99.9%.

The experimental design was developed as a pilot experiment, and the following set-up was proposed with the following number of experimental runs:

- E0: Five experimental runs and a single run between each blend
- E10, E20, E30, E35, E40: Three experimental runs for each concentration

Each fuel blend E{i} test was operated with the fuel flow fixed at 1.1 L/min, which resulted in an engine speed of around 45,000 min$^{-1}$. This means that the whole experiment consisted of fifteen engine runs that could be analysed as a pilot study.

The start-up of the engine was controlled hydromechanically using the compressor pressure p2 output in a proportional fuel flow feedback loop during start-up. After start-up, the fuel flow was kept at a constant level using the fuel pump. The effects of the fuels upon start-up of the engine and during stable operation were investigated separately, as shown in the results. After each run, the engine's fuel system was purged with clean JET A-1 fuel, and the engine was operated once using only clean fuel to purge any remnants of the fuel blend from the engine. The engine in the laboratory was maintained at 18 °C and 60% humidity during all experimental runs.

The basic results and courses of all executed experiments are shown in Table 5. The rows outlined in red show the experiments that were not successful, indicating that the general operation of the engine using the JET A-1/Ethanol fuel blends was problematic. The general rule is to first explore the results when starting the engine after a pause, which seemed to be more problematic using the ethanol blends than when starting with pure kerosene fuel. This was observed in the first start-ups of the engine with the E20 and E30 fuels. Table 5 also shows that the E40 blend was problematic and that the fuel did not have enough power to accelerate the engine above 22,000 min$^{-1}$.

**Table 5.** Experimental logbook *.

| Test Day | Runs | Operational Time (s) | EGT $_{max}$ (°C) | $n_{max}$ ($min^{-1}$) | Tested Blend | Note |
|---|---|---|---|---|---|---|
| 1 | 3 | 30 | 812 | 45,500 | E0 | 3 consecutive runs with E0 |
| 1 | 1 | 30 | 690 | 45,000 | E10 | — |
| 1 | 1 | 10 | 753 | 45,000 | E10 | Run for only 10 s—discarded |
| 1 | 1 | 30 | 735 | 45,000 | E10 | — |
| **Total** | **6** | | | | | **The end of the testing day** |
| 2 | 1 | 30 | 731 | 44,700 | E10 | |
| 2 | 1 | 30 | 602 | 21,000 | E10/E20 | Engine achieved only 20,000 ($min^{-1}$)—discarded |
| 2 | 1 | 30 | 710 | 44,000 | E20 | — |
| 2 | 1 | 30 | 690 | 44,000 | E20 | — |
| **Total** | **10** | | | | | **The end of the testing day** |
| 3 | 1 | 15 | 570 | 19,000 | E20 | Engine achieved only 20,000 ($min^{-1}$)—discarded |
| 3 | 1 | 30 | 716 | 44,000 | E20 | — |
| 3 | 1 | 30 | 703 | 45,000 | E0/E20 | Remnants of the fuel blend caused the speed to rise—discarded |
| **Total** | **13** | | | | | **The end of the testing day** |
| 4 | 1 | 30 | 626 | 43,500 | E30 | Double spike in EGT, difficult startup—discarded |
| 4 | 1 | 30 | 687 | 43,000 | E30 | — |
| 4 | 1 | 30 | 687 | 42,700 | E30 | — |
| 4 | 1 | 30 | 687 | 43,000 | E30 | — |
| 4 | 1 | 50 | 680 | 45,000 | E0/E30 | Remnants of the fuel blend caused the speed to rise from 43k to 45k—discarded |
| **Total** | **18** | | | | | **The end of the testing day** |
| 5 | 1 | 20 | 610 | 17,000 | E40 | Stabilised only at 17,000 ($min^{-1}$) |
| 5 | 1 | 20 | 617 | 22,000 | E40 | Stabilised only at 22,000 ($min^{-1}$) |
| 5 | 1 | 30 | 617 | 22,000 | E40 | Stabilised only at 22,000 ($min^{-1}$) |
| 5 | 1 | 60 | 680 | 45,200 | E0/E40 | Remnants of the fuel blend caused the speed to rise from 21k to 45k—discarded |
| 5 | 1 | 30 | 674 | 42,500 | E35 | — |
| 5 | 1 | 30 | 660 | 42,500 | E35 | — |
| 5 | 1 | 30 | 660 | 42,500 | E35 | — |
| 5 | 1 | 60 | 655 | 45,200 | E0/E35 | Remnants of the fuel blend caused the speed to rise from 21k to 45k—discarded |
| **Total** | **26** | | | | | **The end of the testing day** |

* Red rows indicate measurements which were problematic and not included in the analysis.

## 3. Results

To evaluate the effects of different fuel blends, it was necessary to perform an analysis of the engine's operation separately during its start-up and during a stable operational run. Thus, situational frames for the three engine operational phases were proposed (Figure 6). The start-up phase is defined as Condition (2). The stable operational phase is given as Condition (3). The shutdown phase is initiated both when Condition (4) is met and Condition (2) is false:

$$n(t) \geq 6000\ \text{min}^{-1}\ \boldsymbol{AND} \frac{dn(t)}{dt} \geq 50\ \text{min}^{-1}\text{s}^{-1}\ \boldsymbol{AND}\ \frac{dEGT(t)}{dt} \geq 20\ ^{\circ}\text{Cs}^{-1}\ \boldsymbol{AND}\ t \geq 2\ \text{s} \tag{2}$$

$$\frac{dn(t)}{dt} \in \langle -200; 200 \rangle\ \text{min}^{-1}\text{s}^{-1}\ \boldsymbol{AND}\ \frac{dEGT(t)}{dt} \in \langle -5; 5\ \rangle ^{\circ}\text{Cs}^{-1}\ \boldsymbol{AND}\ n(t) \geq 35\,000\ \text{min}^{-1} \tag{3}$$

$$\frac{dEGT(t)}{dt} \leq -40\ ^{\circ}\text{Cs}^{-1} \boldsymbol{AND} \frac{dn(t)}{dt} \leq -2000\ \text{min}^{-1}\text{s}^{-1} \tag{4}$$

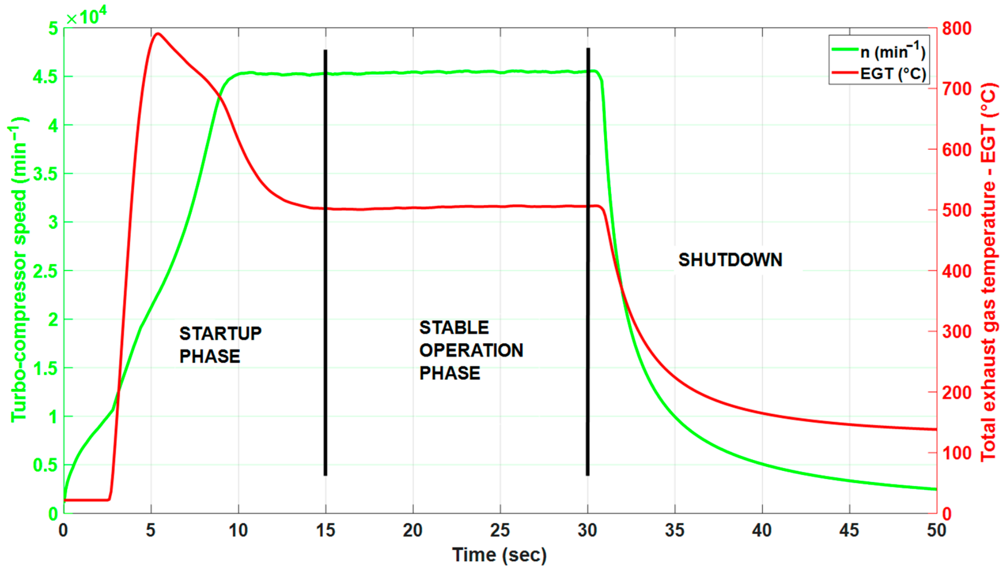


**Figure 6.** An example of the division of the engine's operation into situational frames.

The graph in Figure 6 shows a representative run of the engine using E0 fuel, with EGT peaking at around 800 °C, and the engine running at a constant speed of 45,000 min$^{-1}$ without a speed controller; only the fuel flow is kept at a constant level. Fuel flow was selected to be constant to run the engine in the middle of its power curve and the fuel flow was fixed at flow of 1.1 L/min in all experiments during its stable operational phase. This means that the hydromechanical fuel pump was set to always maintain this fuel level during the stable operation of the engine and environmental conditions. Fuel flow is thus an independent parameter.

During stable operation of the engine, the following basic statistical indicators were computed for each evaluated engine parameter:

$$\text{Mean} \quad \overline{x} = \frac{1}{m}\sum_{i=1}^{m} x_i \tag{5}$$

$$\text{Variance} \quad s^2 = \frac{1}{m-1}\sum_{i=1}^{m}(x_i - \overline{x})^2 \tag{6}$$

$$\text{Standarddeviation} \quad s = \left(\frac{1}{m-1}\sum_{i=1}^{m}(x_i - \overline{x})^2\right)^{\frac{1}{2}} \tag{7}$$

$$\text{Standarderrorofthemean} \quad sE = \frac{\left(\frac{1}{m-1}\sum_{i=1}^{m}(x_i - \overline{x})^2\right)^{\frac{1}{2}}}{\sqrt{m}} \tag{8}$$

where $m$ is the number of samples.

For the start-up situational frame, the following additional indicators were computed:

- Peak time ($t_P$): the time for which the maximum value of variables (peak values) was measured.
- Peak value: the measured value at the peak time.
- Settling time ($t_S$): the time required for the measured (response) curve to reach and stay within a range of ±2% of the steady state (final) value. The settling time is, in our case, defined by Condition (3).
- Integral of value ($A$): In our case, the areas under the curves were computed using the midpoint rule of the numerical integral:

$$A = \Delta x \sum_{i=1}^{l} f(x_i) \quad (9)$$

where $\Delta x$ is the length of the subinterval (step size), $l$ represents the number of samples, and $x_i$ is the midpoint of the $i$th subinterval.

- Overshoot value (percentage overshoot $PO$):

$$PO = \frac{T_p - T_s}{T_s}\ .\ 100\% \quad (10)$$

where $T_p$ is the peak value, and $T_s$ is the settled value.

The basic statistical parameters presented in Tables 6–9 were calculated as follows. Each parameter—mean (5), variance (6), standard deviation (7), and standard error (8)—was computed across three engine runs for the particular JET A-1/Ethanol fuel blend in a stable situational frame. The following sections analyse and present the results of the observed effects during the individual situational frames for all the main investigated parameters of the engine.

**Table 6.** Fuel flow during experiments.

| Indicator / Fuel Blend | Maximum FF (L/min) | Mean(L/min) | Variance | Standard Deviation | Standard Error |
|---|---|---|---|---|---|
| **E0** | 1.166 | 1.130 | 0.0003278 | 0.0181 | $8.5337 \times 10^{-4}$ |
| **E10** | 1.164 | 1.124 | 0.0002135 | 0.0146 | $6.8883 \times 10^{-4}$ |
| **E20** | 1.145 | 1.116 | 0.0002354 | 0.0153 | $7.2324 \times 10^{-4}$ |
| **E30** | 1.136 | 1.117 | 0.0000852 | 0.0092 | $4.3531 \times 10^{-4}$ |
| **E35** | 1.145 | 1.126 | 0.0000477 | 0.0069 | $3.2588 \times 10^{-4}$ |
| **E40** | 0.638 | 0.618 | 0.0001162 | 0.0107 | $6.2240 \times 10^{-4}$ |

**Table 7.** The effect of ethanol/Jet A-1 fuel on stable speed.

| Indicator / Fuel Blend | Maximum Speed ($min^{-1}$) | Mean ($min^{-1}$) | Variance | Standard Deviation | Standard Error |
|---|---|---|---|---|---|
| **E0** | 45556.7 | 45280.9 | 38054.0 | 195.0 | 9.1 |
| **E10** | 44873.2 | 44684.6 | 5963.2 | 77.2 | 3.6 |
| **E20** | 43780.4 | 43514.1 | 22511.4 | 150.0 | 7.0 |
| **E30** | 43299.8 | 42944.4 | 36454.7 | 190.9 | 9.0 |
| **E35** | 43008.0 | 42480.9 | 25084.5 | 158.3 | 7.4 |
| **E40** | 22446.6 | 20251.0 | 3737437.9 | 1933.2 | 111.6 |

**Table 8.** The effect of the alternative fuel on the stable exhaust gas temperature (EGT).

| Fuel Blend \ Indicator | Maximum EGT (°C) | Mean (°C) | Variance | Standard Deviation | Standard Error |
|---|---|---|---|---|---|
| **E0** | 506.7 | 501.4 | 9.4 | 3.0 | 0.17 |
| **E10** | 501.5 | 494.9 | 15.5 | 3.9 | 0.22 |
| **E20** | 489.6 | 487.8 | 1.3 | 1.1 | 0.06 |
| **E30** | 477.7 | 474.4 | 2.2 | 1.4 | 0.08 |
| **E35** | 478.8 | 473.4 | 14.0 | 3.7 | 0.21 |
| **E40** | 510.4 | 487.9 | 69.6 | 8.3 | 0.54 |

**Table 9.** The effect of ethanol/Jet A-1 fuel on stable speed.

| Fuel Blend \ Indicator | Maximum Pressure (atm) | Mean (atm) | Variance | Standard Deviation | Standard Error |
|---|---|---|---|---|---|
| **E0** | 3.434 | 3.366 | 0.001761 | 0.041 | 0.0019 |
| **E10** | 3.280 | 3.243 | 0.000198 | 0.014 | 0.0006 |
| **E20** | 3.118 | 3.071 | 0.000766 | 0.027 | 0.0013 |
| **E30** | 3.052 | 3.007 | 0.000618 | 0.024 | 0.0011 |
| **E35** | 3.033 | 2.947 | 0.000676 | 0.026 | 0.0012 |
| **E40** | 1.418 | 1.334 | 0.005004 | 0.070 | 0.0040 |

### *3.1. The Independent Variable—Fuel Flow*

Fuel flow is an independent parameter of the engine. This parameter was set to a constant level during stable operation of the engine, fixed at 1.1 L/min, and maintained hydro-mechanically. Some small variations in the fuel flow can be observed; however, these variations are at the level of statistical errors, which means that the fuel flow was well-stabilised and did not have any effect on performance and state parameters of the engine. Statistical indicators of variance, standard deviation and standard error have very low and similar values. Because the engine failed to stabilise at a standard idle speed with the E40 fuel, fuel flow with this fuel blend was considerably lower and the statistical indicator show some difference, this state with E40 fuel is analysed in the following chapters. Table 6 and Figure 7 prove that the fuel flow was kept constant during all experiments with very small variations during stable operation of the engine where the effects of fuel are analysed.

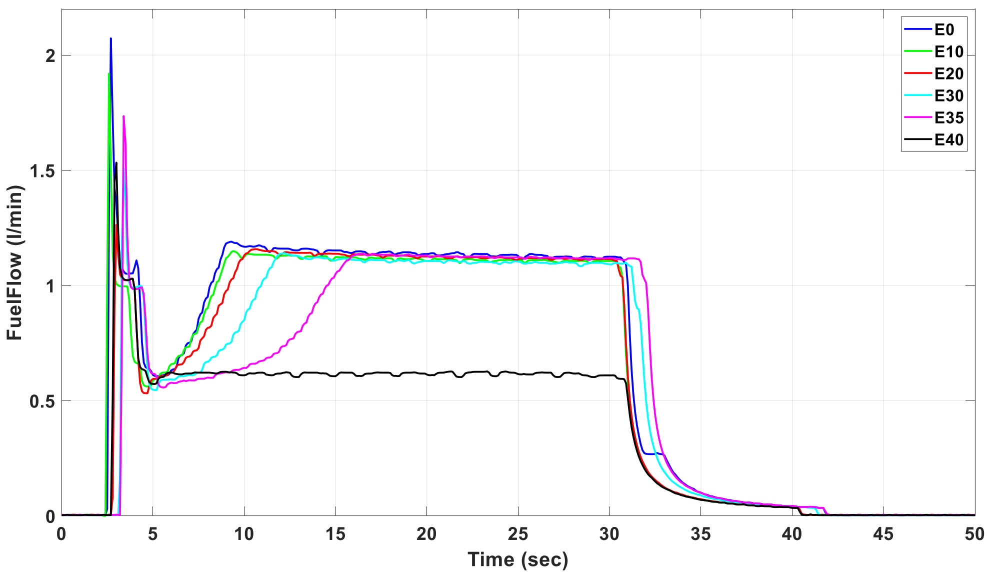


**Figure 7.** Fuel flow during experimental runs of the engine.

### 3.2. The Effect of Alternative Fuel on the Stable Speed of the Engine

The effect of all defined JET A-1/Ethanol fuel blends on the engine's stable speed was evaluated. The stable regime of operation was selected according to the rules defined in Condition (3).

The results of various JET A-1/Ethanol fuel blends on stable engine speed are shown in Table 7. The computed means together with the error bars of the standard deviations are visualised in Figure 8. The main effect observable in the data is that the stable engine speed decreased with an increasing concentration of ethanol in the fuel blend. The variance and standard deviation remained stable, which shows that the engine was running in a stabilised mode and that the ethanol concentration did not affect this stability.

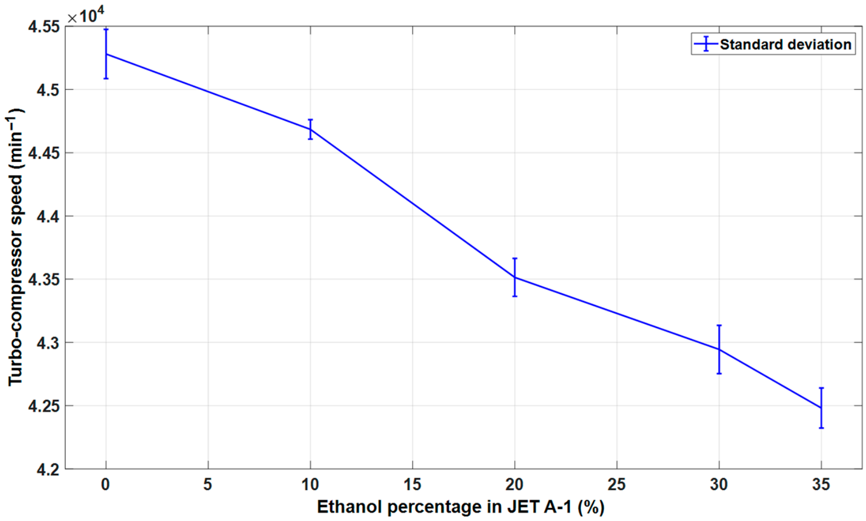


**Figure 8.** Average speed at different fuel blend concentrations during a stable regime of operation.

Some positive effects can be seen with the E10 fuel blend, for which the variance and standard deviation are considerably lower than those for other concentrations. On the other hand, the E40 fuel blend concentration did not allow the engine to run successfully.

The engine ran in a regime outside of the envelope regime for this type of engine with a speed much lower than standard idle speed 35,000 $min^{-1}$. Here, the engine ran in an unstable mode, as can be seen from the high levels of variance and standard deviation. Figure 9 shows the effects of different fuel blends in a single run on speed. Thus, only one run is presented from the three executed runs at each given concentration.

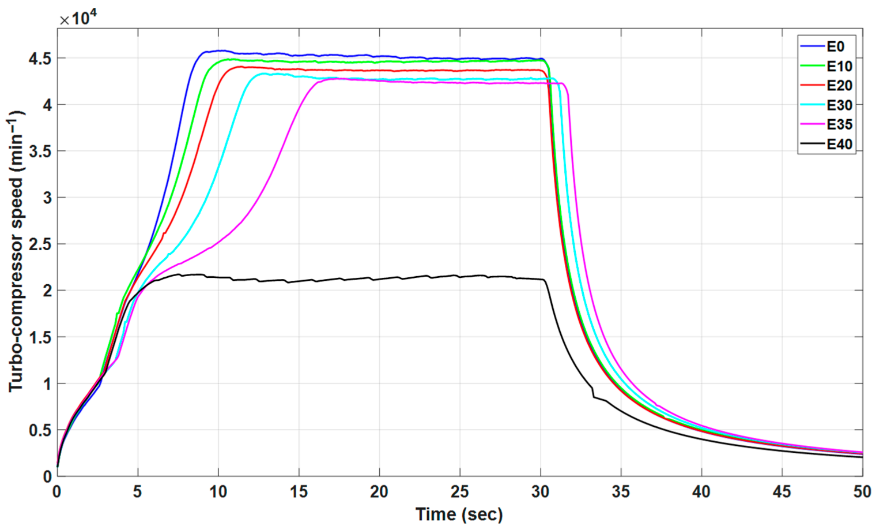


**Figure 9.** Average speed at different fuel blend concentrations during a stable regime of operation.

### 3.3. The Effect of Alternative Fuel on Stable Exhaust Gas Temperature of the Engine

The results of various JET A-1/Ethanol fuel blends on the maximum EGT are shown in Table 8. The computed means together with error bars of the standard deviations are visualised in Figure 10, and a single run for each concentration is shown in Figure 11. Figure 11 shows the effects on speed of different fuel blends in a single run, which means that only one run is presented from three executed runs at each given concentration. The main effect observable in this situational frame is similar to the effect of Jet A-1/Ethanol on speed. It can again be seen that the average exhaust gas temperature decreased with an increase of the ethanol concentration in the fuel. This decrease, however, stopped at concentrations higher than 35%.

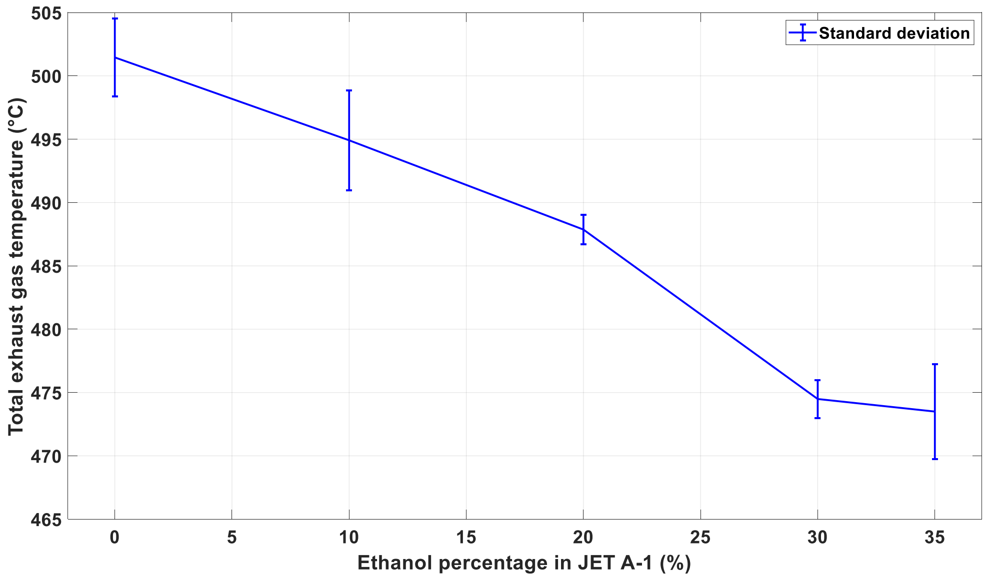


**Figure 10.** Average EGT at different fuel blend concentrations during the stable regime of operation.

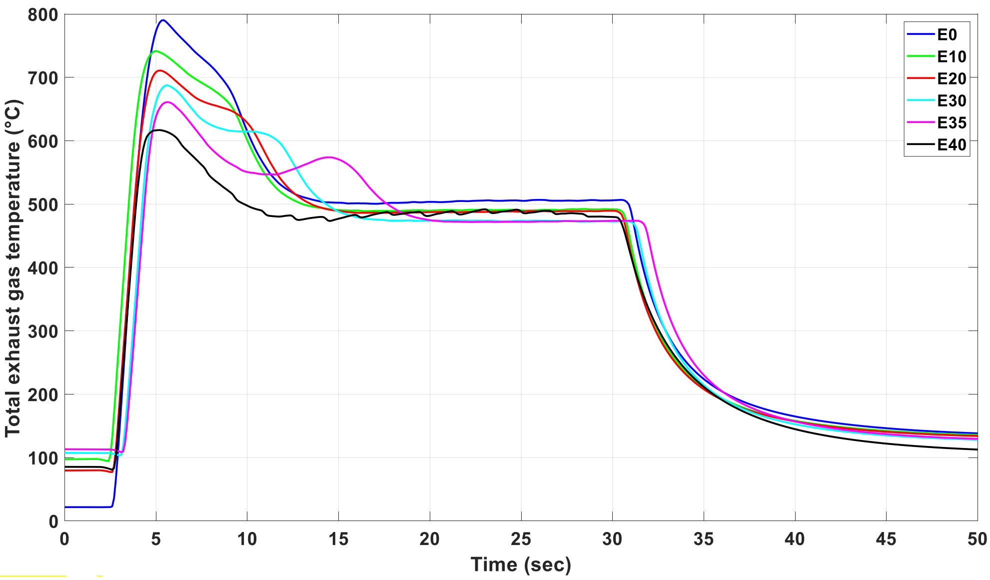


**Figure 11.** EGT during single engine runs at different ethanol concentrations.

At a concentration of 40%, an increase in the maximum and average temperature can be observed because, at this concentration, the engine ran outside of its operational envelope in an unstable manner. Moreover, there was an increase in the standard deviation and standard error at a concentration of 35% because a longer time was required for the engine to stabilise, as shown in Figure 11. It can be concluded that increasing the ethanol concentration in the fuel blend up to a concentration of 35% does not have an adverse effect on the exhaust gas temperature.

### *3.4. The Effect of Alternative Fuel on the Stable Compressor Pressure of the Engine*

The total pressure measured behind the compressor shows similar behaviour to the speed of the engine because both parameters are connected under constant environmental (laboratory) conditions. The total pressure decreased with an increase of the ethanol concentration in the fuel; this can be observed in Table 9 and is graphically illustrated in Figure 12. The variance, standard deviation, and standard error of the mean are low, which means that the effects are valid. A decrease in the total pressure during operation of the engine can be also seen in the time plot shown in Figure 13 for single concentrations. For E40 concentrations, again, the engine clearly ran in an unstable regime of operation.

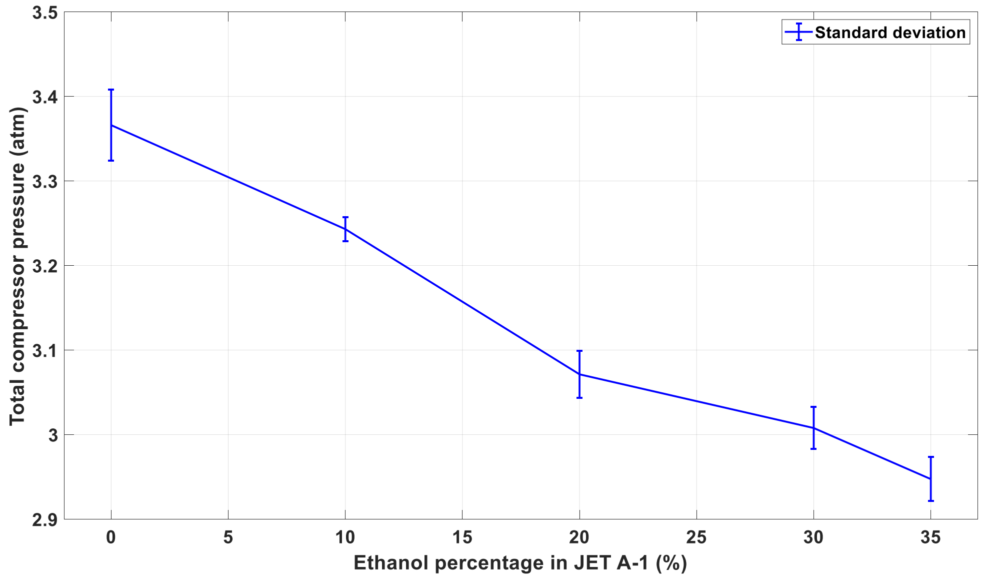


**Figure 12.** Average compressor pressure at different fuel blend concentrations during the stable regime of operation.

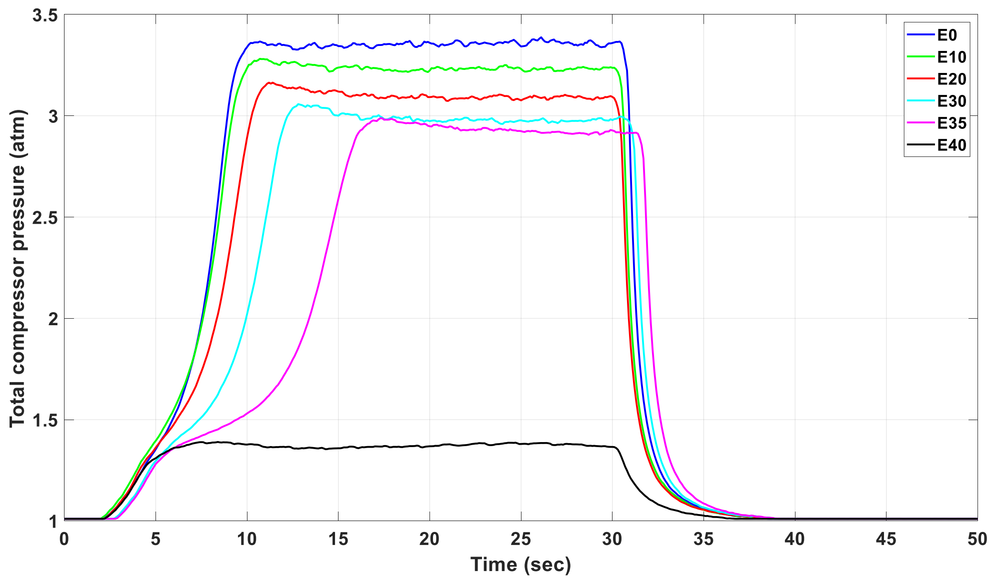


**Figure 13.** Compressor pressure during single engine runs at different ethanol concentrations.

### 3.5. The Effect of Alternative Fuel on the Start-Up of the Engine

The start-up phase of any jet engine plays a critical role in its technical life and performance. This phase places a high strain on the components of the engine. This strain is defined mainly by the temperature and rotational speed. The effects of alternative fuel on these parameters were, therefore, investigated. The temperature strain on a jet engine during its start-up is mostly characterised by the engine's peak temperature, which is obtained during start-up (Peak EGT). It is also important to evaluate how much total heat the components of the engine absorb during this phase. This can be done by computing the integral value of the EGT during the phase according to Equation (9). The other parameters tied to the absorbed heat are the times at which the temperature reaches its maximum and the settling time.

The settling time defines how long it takes the temperature to stabilise. The last parameter tied to the peak value of EGT is the overshoot value, which defines how far the peak was from the stabilised temperature value. In terms of temperature strain, these parameters can give a good picture of thermal strain during start-up. The results from three runs for each fuel blend concentration are shown in Table 10. The mean value from all three runs was also computed, and the results for the integral and peak values of EGT are visualised in Figures 14 and 15.

With an increase of the ethanol concentration in the fuel blend, the peak value of EGT decreased, as seen in Figure 15. This decrease was around 130 °C, which is a significant value. This can be evaluated as a positive effect of ethanol on the operation of a small turbojet engine. On the other hand, the integral value of EGT increased during start-up, as shown in Figure 14. This means that the engine experienced high temperatures during start-up for a longer time. The positive effect of lowering the temperature peak was, therefore, somewhat negated by the higher integral value and total heat energy absorbed by the engine during start-up.

**Table 10.** Exhaust gas temperature during the start-up phase.

| Fuel Blend \ Parameter | No. of Measurement | Integral Value (°C.sec) | Peak EGT (°C) | Mean EGT (°C) | Peak Time (sec) | Settling Time (sec) | Overshoot Value (%) |
|---|---|---|---|---|---|---|---|
| E0 | 1. | 7074.2 | 790.4 | 504.2 | 2.70 | 10.09 | 56.7 |
| | 2. | 7455.0 | 813.0 | 500.9 | 2.90 | 10.26 | 62.3 |
| | 3. | 6133.6 | 769.8 | 498.3 | 3 | 9.07 | 54.4 |
| Mean | | 6887.6 | 791.1 | 501.1 | 2.86 | 9.81 | 57.8 |
| E10 | 1. | 7198.5 | 677.7 | 492.6 | 2.30 | 10.69 | 37.5 |
| | 2. | 7529.3 | 741.5 | 490.7 | 2.70 | 10.87 | 51.1 |
| | 3. | 7159.0 | 731.5 | 499.7 | 2.40 | 10.06 | 46.3 |
| Mean | | 7295.6 | 716.9 | 494.3 | 2.46 | 10.54 | 45.0 |
| E20 | 1. | 7662.4 | 710.9 | 487.9 | 2.50 | 11.16 | 45.6 |
| | 2. | 7559.2 | 691.8 | 486.0 | 2.50 | 11.72 | 42.3 |
| | 3. | 8145.7 | 718.0 | 488.0 | 2.80 | 11.71 | 47.1 |
| Mean | | 7789.1 | 706.9 | 487.3 | 2.6 | 11.53 | 45.0 |
| E30 | 1. | 7900.9 | 688.0 | 477.1 | 2.50 | 11.91 | 44.2 |
| | 2. | 8163.8 | 687.6 | 473.8 | 2.50 | 12.67 | 45.1 |
| | 3. | 7964.6 | 681.8 | 473.7 | 2.60 | 12.72 | 43.9 |
| Mean | | 8009.7 | 685.8 | 474.8 | 2.53 | 12.43 | 44.4 |
| E35 | 1. | 7905.6 | 674.7 | 478.3 | 2.60 | 12.66 | 41.0 |
| | 2. | 9503.8 | 660.9 | 472.7 | 2.40 | 15.91 | 39.8 |
| | 3. | 9974.9 | 661.2 | 469.3 | 2.40 | 16.53 | 40.8 |
| Mean | | 9128.1 | 665.6 | 473.4 | 2.46 | 15.03 | 40.5 |
| E40 | 1. | 3753.5 | 610.6 | 496.9 | 2.20 | 5.79 | 22.8 |
| | 2. | 5306.4 | 614.1 | 480.3 | 2.80 | 8.52 | 27.8 |
| | 3. | 4645.2 | 616.8 | 486.5 | 2.50 | 7.52 | 26.7 |
| Mean | | 4568.3 | 613.8 | 487.9 | 2.5 | 7.28 | 25.8 |

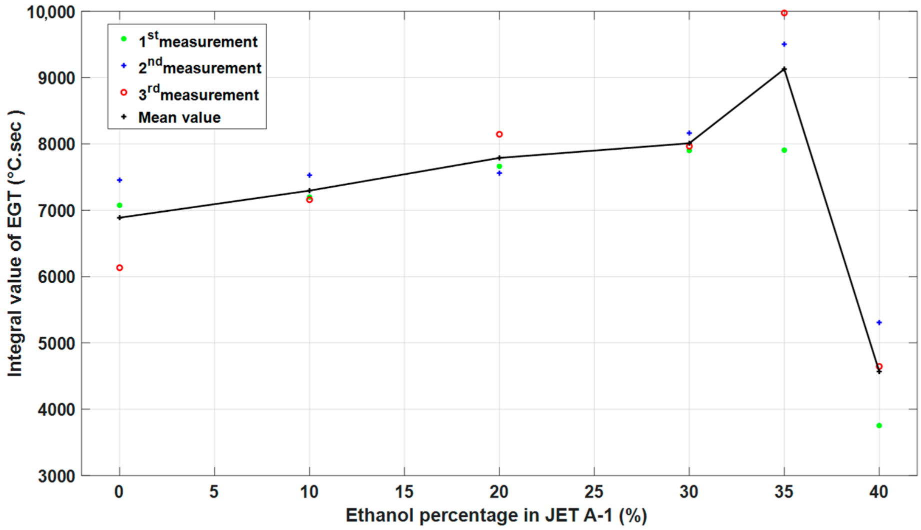


**Figure 14.** Integral value of the exhaust gas temperature during start-up.

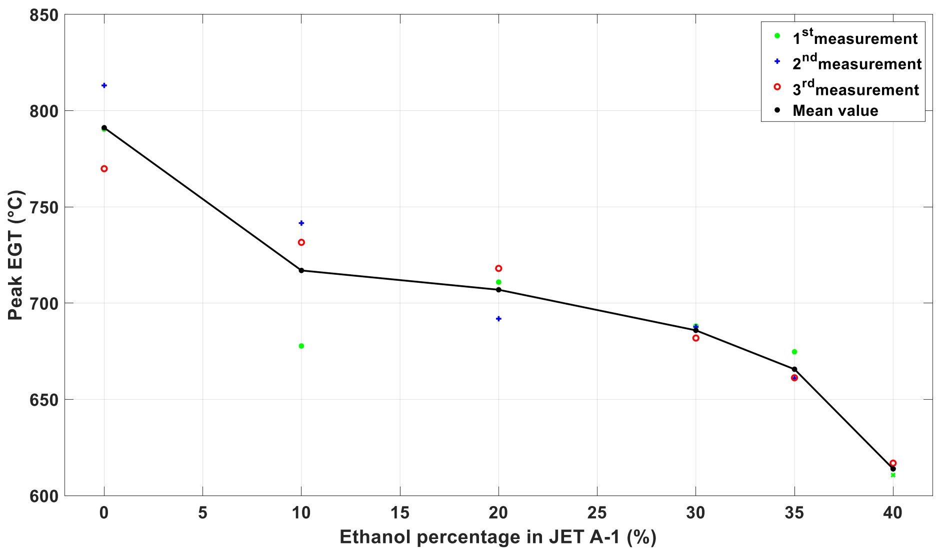


**Figure 15.** Peak value of the exhaust gas temperature during start-up.

The effects of ethanol in jet fuel on performance were investigated by analysing the rotational speed of the engine during the start-up phase. One of the most important parameters in jet engines is their starting time. This settling time is shown in Figure 16. When using clean JET A-1 fuel, the engine was able to start in 6 s. By increasing the ethanol concentration in the fuel blend, the starting time increased considerably, being the worst at a concentration of 35%. With the concentration of ethanol at the level of 40%, the starting time was shorter. However, the engine's speed reached only the sub-idle level. It can be concluded that an increase in the ethanol concentration has a detrimental impact on engine starting times.

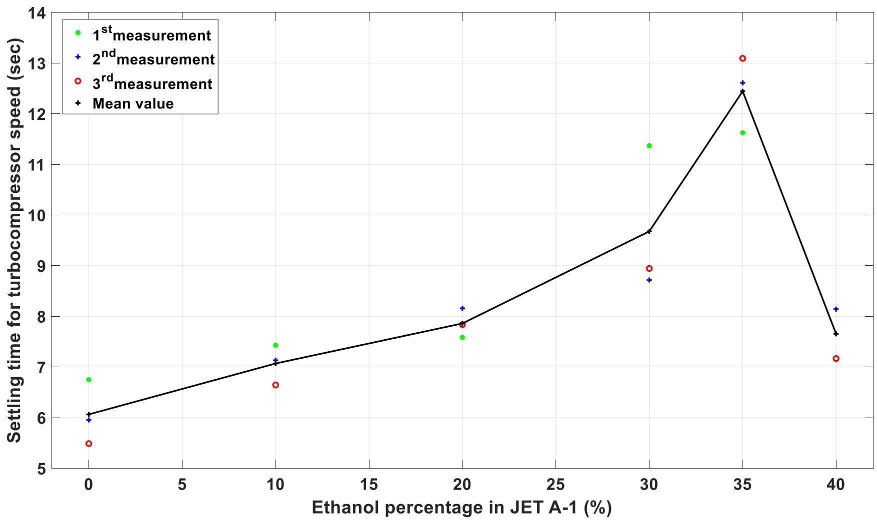


**Figure 16.** Starting time of a small turbojet engine with different ethanol concentrations.

In general, it can be concluded that the effects of ethanol in JET A-1 fuel are generally adverse during the start-up phase of the engine. Ethanol prolongs the initialisation of the engine up to the point that the speed of the engine hangs below its idle speed. The positive effect of ethanol is its ability to decrease the peak temperature during start-up, which could be beneficial for the materials of turbine blades.

## 4. Discussion

The present study explored some effects of the application of JET A-1/ethanol blends in small turbojet engines. These fuel blends provide less gross heat energy than clean JET A-1 fuel, so some performance drops were expected. These results are valid for a class of single stream turbojet engines, but our conclusion will likely also be valid for larger turbojet engines.

We found that this type of engine with a hydromechanical fuel control system is not able run with concentrations of ethanol higher than 40% in the fuel blend. All other effects were analysed in two basic situational frames: the start-up and stable regime of operation. It was found that during the stable operation of the engine, the ethanol in the fuel caused a drop in the stable operating speed of the engine, a drop in the exhaust gas temperature, and, consequently, a decrease in the pressure behind the compressor. With a concentration of 35% percent of ethanol in the fuel blend, the speed dropped by 7500 $min^{-1}$ at a constant fuel flow. This means that ethanol, as expected, has a negative impact on the performance of a turbojet engine but that the engine is still able to run in a stable manner at such a concentration.

The effects of ethanol on the start-up of the engine were also negative, causing the start-up to last longer and increasing the total temperature load on the components of the engine. The positive effect of ethanol was that the engine peaked at a lower exhaust gas temperature during start-up, which could have a positive effect on the lifetime durability of the turbine blades.

Most of these effects could likely be offset via the implementation of digital fuel control systems and speed control algorithms. In this way, the thrust output of the engine could be increased and maintained at a desired level, albeit at the cost of increased fuel consumption. The results show that ethanol is a viable additive to JET A-1 fuel; however, this addition decreases the performance of the turbojet engine and increases fuel consumption, if the performance remains a constant level.

Given this result, the hypothesis for emissions of the engine is not clear and should be explored in follow-up experiments for the concentrations of ethanol in JET A-1 investigated in this study for this class of engines. Ethanol as fuel additive might also negatively impact seals in fuel and lubrication systems of turbojet engines [44], which is another area that needs to be further tested specifically for every engine where JET A-1 fuel with ethanol is applied. On the other hand, some additives might solve these problems like investigated in [45].

We can thus conclude that it is operationally possible to use ethanol JET A-1 fuel blend with ethanol concentrations up to 35% for small single stream turbojet engines with radial compressors, but the effects on emissions, seals, and other components need to be researched further in long term testing.

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## Abbreviations

| | |
|---|---|
| 2-EH | 2-Ethylhexanol |
| AVGAS | Aviation Gas |
| CO | Carbon Monoxide |
| CO2 | Carbon Dioxide |
| E | Ethanol |
| EGT | Exhaust Gas Temperature |
| FF | Fuel Flow |
| GHG | Greenhouse Gas |
| H2O | Water |
| HC | Hydrocarbon |
| HEFA | Hydro-processed Esters and Fatty Acids |
| HHV | Higher Heating Value |
| JET A | Jet Fuel |
| MPM-20 | Small Turbojet Engine |
| n | Rotational Speed of the Engine |
| N2 | Nitrogen |
| NI | National Instruments |
| NOx | Nitrogen Oxide |
| p2 | Total Compressor Pressure |
| PL | Phase Level |
| PM | Particulate Matter |
| PME | Palm Methyl Ester |
| PR | Phase Range |
| SPK | Synthesized Paraffinic Kerosene |

## References


1. Greenhouse Gas Emission Statistics-Emission Inventories. Available online: https://ec.europa.eu/eurostat/statistics-explained/pdfscache/1180.pdf (accessed on 25 February 2021).
2. Blakey, S.; Rye, L.; Wilson, C.W. Aviation gas turbine alternative fuels: A review. *Proc. Combust. Inst.* **2011**, *33*, 2863–2885. [CrossRef]
3. Airbus–Global Market Forecast. Available online: https://www.airbus.com/content/dam/corporate-topics/financial-and-company-information/GMF-2019-Press-Release.pdf (accessed on 15 April 2020).
4. Wei, H.; Liu, W.; Chen, X.; Yang, Q.; Li, J.; Chen, H. Renewable bio-jet fuel production for aviation: A review. *Fuel* **2019**, *254*. [CrossRef]
5. Turner, J.; Lewis, A.G.; Akehurst, S.; Brace, C.J.; Verhelst, S.; Vancoillie, J.; Sileghem, L.; Leach, F.; Edwards, P.P. Alcohol fuels for spark-ignition engines: Performance, efficiency and emission effects at mid to high blend rates for binary mixtures and pure components. *Automob. Eng.* **2018**, *232*, 36–56. [CrossRef]
6. Tian, Z.; Zhen, X.; Wang, Y.; Liu, D.; Li, X. Comparative study on combustion and emission characteristics of methanol, ethanol and butanol fuel in TISI engine. *Fuel* **2020**, *259*. [CrossRef]
7. Dandu, M.S.R.; Nanthagopal, K. Tribological aspects of biofuels–A review. *Fuel* **2019**, *258*, 116066. [CrossRef]
8. Turner, J.W.G.; Pearson, R.J.; Holland, B.; Peck, R. Alcohol-based fuels in high performance engines. *SAE Trans.* **2007**, 55–69. [CrossRef]
9. Goldemberg, J. The ethanol program in Brazil. *Environ. Res. Lett.* **2006**, *1*, 014008. [CrossRef]
10. De Oliveira, F.C.; Coelho, S.T. History, evolution, and environmental impact of biodiesel in Brazil: A Review. *Renew. Sustain. Energy Rev.* **2017**, *75*, 168–179. [CrossRef]
11. Grahn, M.; Hansson, J. Prospects for domestic biofuels for transport in Sweden 2030 based on current production and future plans. *Wiley Interdiscip. Rev. Energy Environ.* **2015**, *4*, 290–306. [CrossRef]
12. De Simio, L.; Gambino, M.; Iannaccone, S. Effect of ethanol content on thermal efficiency of a spark-ignition light-duty engine. *ISRN Renew. Energy* **2012**. [CrossRef]
13. Tibaquirá, J.E.; Huertas, J.I.; Ospina, S.; Quirama, L.F.; Niño, J.E. The effect of using ethanol-gasoline blends on the mechanical, energy and environmental performance of in-use vehicles. *Energies* **2018**, *11*, 221. [CrossRef]
14. Myung, C.-L.; Choi, K.; Cho, J.; Kim, K.; Baek, S.; Lim, Y.; Park, S. Evaluation of regulated, particulate, and BTEX emissions inventories from a gasoline direct injection passenger car with various ethanol blended fuels under urban and rural driving cycles in Korea. *Fuel* **2020**, *262*. [CrossRef]
15. Sandalcı, T.; Karagöz, Y.; Orak, E.; Yüksek, L. An experimental investigation of ethanol-diesel blends on performance and exhaust emissions of diesel engines. *Adv. Mech. Eng.* **2014**, *6*. [CrossRef]
16. Labeckas, G.; Slavinskas, S.; Laurinaitis, K. Effect of jet A-1/ethanol fuel blend on HCCI combustion and exhaust emissions. *J. Energy Eng.* **2018**, *144*. [CrossRef]
17. Chen, L.; Zhang, Z.; Lu, Y.; Zhang, C.; Zhang, X.; Zhang, C.; Roskilly, A.P. Experimental study of the gaseous and particulate matter emissions from a gas turbine combustor burning butyl butyrate and ethanol blends. *Appl. Energy* **2017**, *195*, 693–701. [CrossRef]
18. Shauck, M.E.; Tubbs, J.; Zanin, M.G. Certification of a Carburater Aircraft Engine on Ethanol Fuel. Available online: https://afdc.energy.gov/files/pdfs/2896.pdf (accessed on 25 February 2021).
19. Iliev, S. A Comparison of Ethanol, Methanol and Butanol Blending with Gasoline and Relationship with Engine Performances and Emissions. *Ann. DAAAM Proc.* **2018**, *29*. [CrossRef]
20. Huynh, T.T.; Le, M.D.; Duong, D.N. Effects of butanol–gasoline blends on SI engine performance, fuel consumption, and emission characteristics at partial engine speeds. *Int. J. Energy Environ. Eng.* **2019**, *10*, 483–492. [CrossRef]
21. Litt, J.S.; Chin, J.C.; Liu, Y. *Simulating the Use of Alternative Fuels in a Turbofan Engine*; National Aeronautics and Space Administration, Glenn Research Center: Cleveland, OH, USA, 2013.
22. Gawron, B.; Białecki, T.; Dzięgielewski, W.; Kaźmierczak, U. Performance and emission characteristic of miniature turbojet engine FED Jet A-1/alcohol blend. *J. KONES* **2016**, *23*. [CrossRef]
23. Mendez, C.J.; Parthasarathy, R.N.; Gollahalli, S.R. Performance and emission characteristics of butanol/Jet A blends in a gas turbine engine. *Appl. Energy* **2014**, *118*, 135–140. [CrossRef]
24. Gawron, B.; Białecki, T. Impact of a Jet A-1/HEFA blend on the performance and emission characteristics of a miniature turbojet engine. *Int. J. Environ. Sci. Technol.* **2018**, *15*, 1501–1508. [CrossRef]
25. Yang, J.; Xin, Z.; Corscadden, K.; Niu, H. An overview on performance characteristics of bio-jet fuels. *Fuel* **2018**, *237*, 916–936. [CrossRef]
26. Vivian, J.; Seeber, A.; Dorrington, G.E. Tests of alternative fuel blends in micro-turbojet engines. In *Asia-Pacific International Symposium on Aerospace Technology*; Engineers Australia: Cairns, Australia, 2015.
27. Gawron, B.; Białecki, T.; Król, A. The effect of adding 2-ethylhexanol to jet fuel on the performance and combustion characteristics of a miniature turbojet engine. *J. Kones* **2018**, *25*, 101–109. [CrossRef]
28. Gires, E.; Abu Talib, A.R.; Ahmad, M.T.; Idris, A. Performance test of a small-scale turbojet engine running on a palm oil biodiesel-jet a blend. In Proceedings of the 28th International Congress of the Aeronautical Sciences, Brisbane, Australia, 23–28 September 2012. [CrossRef]

29. Mendez, C.; Parthasarathy, R.; Gollahalli, S. Performance and emission characteristics of a small-scale gas turbine engine fueled with ethanol/Jet A blends. In Proceedings of the 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, 9–12 January 2012. [CrossRef]
30. Yakovlieva, A.; Boichenko, S.; Lejda, K. Evaluation of jet engine operation parameters using conventional and alternative jet fuels. *Int. J. Sustain. Aviat.* **2019**, *5*, 230–248. [CrossRef]
31. Főző, L.; Andoga, R.; Madarász, L. Mathematical model of a small Turbojet Engine MPM-20. In *Studies in Computational Intelligence vol. 313: International Symposium of Hungarian Researchers on Computational Intelligence and Informatics*; Springer: Heidelberg, Germany, 2010; pp. 313–322. ISBN 978-3-642-15220-7-. [CrossRef]
32. Andoga, R.; Madarász, L.; Fozo, L.; Lazar, T.; Gašpar, V. Innovative approaches in modeling, control and diagnostics of small turbojet engines. *Acta Polytech. Hung.* **2013**, *10*, 81–99. [CrossRef]
33. Minteer, S. (Ed.) *Alcoholic Fuels*; CRC Press Taylor & Francis Group 6000 Broken Sound Parkway NW, Suite 300: Boca Raton, FL, USA, 2006; p. 130. ISBN 0-8493-3944-8.
34. Basile, A.; Iulianelli, A.; Dalena, F.; Veziroglu, T.N. *Ethanol*; Elsevier: Amsterdam, The Netherlands, 2018; ISBN 9780128114582.
35. Ha, D.M.; Park, S.H.; Lee, S. The Measurement of Flash Point of Water-Methanol and Water-Ethanol Systems Using Seta Flash Closed Cup Tester. *Fire Sci. Eng.* **2015**, *29*, 39–43. [CrossRef]
36. Torres-Jimenez, E.; Svoljsăak-Jerman, M.; Gregorc, A.; Lisec, I.; Dorado, M.P.; Kegl, B. Physical and chemical properties of ethanol− biodiesel blends for diesel engines. *Energy Fuels* **2010**, *24*. [CrossRef]
37. Madarász, L.; Andoga, R.; Fozo, L. Intelligent Technologies in Modeling and Control of Turbojet Engines. In *New Trends in Technologies: Control, Management, Computational Intelligence and Network Systems*; IntechOpen: London, UK, 2010. [CrossRef]
38. Standard: Crude Petroleum and Petroleum Products. Determination of Density. Oscillation U-Tube Method. Available online: https://www.mystandards.biz/standard/stneniso-12185-1.9.2001.html (accessed on 15 February 2021).
39. Standard: Petroleum Products. Transparent and Opaque Liquids. Determination of Kinematic Viscosity and Calculation of Dynamic Viscosity. Available online: https://stn-online.sk/eshop/public/standard_detail.aspx?id=95790&p=true (accessed on 15 February 2021).
40. Standard: Petroleum Products. Determination of Distillation Characteristics at Atmospheric Pressure. Available online: https://www.mystandards.biz/standard/stneniso-3405-1.8.2011.html (accessed on 15 February 2021).
41. Jaffe, R.L.; Taylor, W. *The Physics of Energy*; Cambridge University Press: Cambridge, UK, 2018. [CrossRef]
42. BS EN ISO 1716:2018: Reaction to Fire Tests for Products—Determination of the Gross Heat of Combustion (Calorific Value). Standard: HongKong, China, 2018.
43. Standard Specification for Aviation Turbine Fuels. Available online: https://www.astm.org/Standards/D1655.htm (accessed on 15 February 2021).
44. Ertekin, A.; Sridhar, N. *Performance of Elastomeric Materials in Gasoline-Ethanol Blends- a Review*; National Association of Corrosion Engineers: Houston, TX, USA, 2009.
45. Boichenko, S.; Lejda, K.; Yakovlieva, A.; Kuszewski, H.; Vovk, O. Experimental study on antiwear properties for blends of jet fuel with bio-components derived from rapeseed oil. *Prace Inst. Lotnictwa* **2016**. [CrossRef]