Alternative Fuels for Small-scale Turbojet Engines: A Review.

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***Abstract*—This paper presents a brief review on the alternative aviation fuels and their impact on small-scale turbojet engines. In addition, perspective alternative fuels for each transport sector are presented, highlighting the advantages and disadvantages of these fuels. Individual production pathways certified for alternative aviation fuels are described, while the maximum possible percentage of these fuels is also indicated.**

Keywords*—alternative fuels, certification, small turbojet engines

I. INTRODUCTION

Humanity is currently dependent mainly on terrestrial sources of energy. Up to 80% of these resources are in the form of fossil fuels such as coal, crude-oil and natural gas (NG) [1]. However, the burning of these fuels creates the main component of atmospheric pollution – nitrogen oxides (NOX), sulfur oxides (SO_X), carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (PM). Greenhouse gases (GHG) – CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and sodium trifluoride (NF_3), resulting from the combustion of petroleum products, are demonstrably involved in climate change [2]. GHG emissions accounted for 25% of all emissions in Europe in 2017 [3]. Atmospheric pollution also has an extremely negative effect on the health of the population. It is estimated that 8.7 million people die annually in the world as a result of fossil-fuel–generated particulate air pollution [4]. According to [5], air pollution from fossil fuels has a negative impact on the neuro-developmental effects on babies and children. Another problem with these fuels is their limited reserves. According to [6], fossil fuel reserve depletion times for oil, coal and gas are approximately 35, 107 and 37 years, respectively (the study was performed in 2009). For these reasons, there is growing pressure to develop new types of fuels that would eliminate the disadvantages of traditional fuels.

The history of alternative fuels begins in 1907, when fuels with the addition of alcohol were first used in the automobile industry [7]. The most significant boom in alternative fuels occurred in the 80s of the 20th century, as a result of the introduction of emissions regulations – in Japan (1966), in the USA (1968), in the EU (1970) [8]. The biggest pioneers in the use of alcohol for automobiles were Brazil and Sweden, which currently use a mixture of gasoline and ethanol in the proportions 75:25 (E25), 15:85 (E85), and also pure ethanol (E100). Currently, alternative fuels are emerging in other transport sectors –marine, truck, railroad, and aviation.

The paper does not concern with electric (battery, hybrid-electric and fuel cells) propulsion as an alternative way to reduce local emissions. Such a survey is elaborated in [9]. The paper is organised as follows: Chapter 2 deals with several types of fuels used in transportation. Chapter 3 deals with crude-oil derived and alternative aviation fuels, and its certification. Chapter 4 deals with alternative fuels for small-scaled turbo-compressor engines and their influence on engine's performance. Chapter 5 conclude the paper.

II. FUELS IN TRANSPORTATION

A. Marine Transportation

Today, the vast majority of marine vessels use heavy fuel oil (HFO). There are two types of HFO – distillate and residual oil (tar), both form during distillation process of crude-oil. Vessels operating in harbours use mainly marine gas oil (MGO) or of marine diesel oil (MDO) [10]. However, all oil derived fuels have big content of sulphur. According to standard ISO 8217:2012, there are fifteen distinct types of approved marine fuels [11].

Liquefied natural gas (LNG), due to its properties (no sulphur content, high hydrogen-to-carbon ratio, eliminates the emission of PM) and relatively low purchase price, is a main alternative fuel for marine transportation. The main disadvantage of LNG is its corrosiveness.

Incorporation of biofuels into the oil derived fuels is also feasible. Fatty acid methyl ester (FAME) is biodiesel derived from renewable sources, such as vegetable oils or animal fats or waste cooking oils by transesterification. Neat FAME, marked as B100, means there is no presence of crude-oil derived diesel in it. It is considered as a possible substitute of conventional marine diesel fuel. Biodiesels have a better lubricity properties compared to traditional diesel. The drawback of biodiesels is its degradation over time to components which are harmful to non-metallic parts of engines [12]. Biofuel produced from biomass (BTL) can be, according to EN ISO 8217-2017, blended with marine distilled fuel.

B. Truck Transportation

The vast majority of current trucks use a diesel engine. By burning crude-oil derived diesel, mainly harmful PM, NO_x and SO_x emissions are produced. For this reason, since 2016

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ultra-low-sulphur diesel (ULSD), which is a diesel fuel with substantially lowered sulphur contents (10–15 ppm), has been preferred in the USA, UK and EU [13]. There are several types of diesel: traditional (petroleum) diesel, biodiesel and synthetic diesel.

Petroleum diesel is the most common type of diesel. It is made by fractional distillation of crude-oil at 200 – 350 °C, at atmospheric pressure. Synthetic diesel can be produced from any carbonaceous material, not restricted only to animal or vegetable sources. Biodiesel is made from vegetable oils (84%), animal fats (10%) and recycled (restaurant) oils (10%) [14]. The biodiesel production process is either through traditional chemical catalysts or transesterification. Biodiesel for diesel trucks and cars is blended with petroleum diesel in several ratios – B7 is used in EU and contains 7% of biodiesel, B10 is used in Argentina (10% of biodiesel), B20 is used in USA (20% of biodiesel).

There are studies, that use blend of hydrogen and diesel to reduce the total amount of emissions [15, 16], blend of NG and diesel to enhance combustion process [17], or blend alcohol with diesel to enhance workflow performance [18, 19].

C. *Railroad Transportation*

From the 19th century, the first railway locomotives used a steam engine, whose energy source was coal. However, such a drivetrain produced a lot of smoke, which was undesirable especially in urban areas. Due to polluted air, a powerful anti-smoke movement arose in Chicago in the early 1900s, demanding for electrification [20]. Even though modern trains are electrified, there are still many locations and uses where electrification is unprofitable. In such cases, diesel-electric locomotives have been used since the 1920s. However, even this concept created an unbearable amount of harmful substances, as already mentioned in the previous chapters. As a result, train drivers developed lung cancer [21]. Currently, diesel locomotives are subject to similar rules as heavy duty trucks, including the use of ULSD.

There are more studies which investigates alternative fuels as a replacement for crude-oil derived diesel. In [22] authors investigate liquefied petroleum gas (LPG) in terms of cost, availability, and methods of adaptation to present locomotive engines. In [23], authors discuss the issue of LNG application for railroad in USA. Biodiesel is also considered as an alternative fuel for railroads [24, 25].

III. FUELS IN AVIATION

Use Aircraft use two basic types of engines – piston and turbo-compressor. Piston engines use gasoline-based fuel called Aviation gasoline (AVGAS). Turbo-compressor engines use several kerosene-based fuels: JET-A, JET-A-1, JP-5, JP-8, TS-1 or a mixture of gasoline and kerosene referred to as JET-B.

JET-A is a typical fuel for turbofan and turboprop aircraft in North America. It is distilled from crude-oil in kerosene fraction. Its freezing point is higher compared to JET-A-1 fuel, -40 °C and -47 °C, respectively. JET-A-1 fuel is most widespread aviation fuel for turbofan and turboprop aircraft. JET-A and JET-A-1 are interchangeable. They have low volatility and low vapor pressure. Flashpoints range between 43 °C and 65 °C. JET-A-1 contains extra anti-static additives. JET-B as a blend of gasoline (70%) and kerosene (30%) has its volatility and vapor pressure in between of these two fuels. JET-B is available in countries with cold environment as Alaska and Canada, due to its low freezing point -60 °C and relatively high volatility. JP-5 is used primarily for military applications, especially for aircraft carriers, due to its high flash point of 60 °C. JP-8 is used by NATO air forces. It contains anti-corrosion additives and anti-icing agents. In Russia, TS-1 fuel is predominantly used. It has lower freezing point than JET-A-1, which makes it suitable for use in harsh Siberian climate. Chinese aviation fuels are numbered No.1 – No.5. No.1 and No.2 fuels are similar to TS-1 fuel. No.3 fuel is equivalent to Jet A-1. No.4 fuel is similar to Jet-B and No.5 fuel is similar to JP-5. [26, 27, 28]

A. *Alternative Fuels in Aviation*

Due to the fact that all aviation fuels mentioned in previous chapter are crude-oil based products, there is a strong press of governments and international organisations to use fuels which are less harmful to environment [29, 30]. One of the largest regulation is ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which was approved in 2016 and is aimed to reduce emissions from international aviation [31, 32].

Currently, there are several ways how to comply with strict emission regulations. One way is to use alternative propulsion system, e.g., in the form of electric drive [33, 34, 35, 36]. Another, more realistic way, especially for large aircraft in the near future, is to retain original turbo-compressor engine and use more eco-friendly fuels. Current aviation JET fuel contains fossil-based low carbon aviation fuel (LCAF). LCAF, according to American Society for Testing Materials (ASTM), can be blended (Tab. 1) with sustainable aviation fuel (SAF). The standard regulating the technical certification of SAF is ASTM D7566 [37]. SAF is an alternative fuel which can be produced from waste oil or fats, green and municipal waste and non-food crops [38]. It can also be produced synthetically via a process that captures carbon directly from the air. SAF reduces CO_2 emissions by up to 80% [39].

TABLE I. MAXIMUM BLENDING RATIO OF SAF AND CRUDE-DERIVED FUEL

Technology	**Maximum blending**
Fischer-Tropsch (FT)	50%
Hydro-processed esters and fatty acids (HEFA)	50%
Hydro-processed Hydrocarbons – synthetic paraffinic kerosene (HH-SPK)	10%
Synthetic Iso-Paraffins (SIP)	10%
Alcohol to jet – synthetic kerosene with aromatics (ATJ-SKA)	50%
Alcohol to jet – synthetic paraffinic kerosene (ATJ-SPK)	30%
Catalytic Hydro-thermolysis Jet fuel (CHJ)	50%

B. *Alternative Aviation Fuel Certification*

There are seven production pathways certified to produce SAF (Tab. 2) and other technologies are currently under the evaluation by ASTM [40, 41, 42, 43].

Fischer-Tropsch synthesized isoparaffinic kerosene (FT-SPK) was approved by ASTM in 2009. In the FT-SPK process, coal, natural gas, or biomass feed stocks are gasified into a syngas comprised of hydrogen and CO, then it is catalytically converted to a liquid hydrocarbon fuel [40].

Synthesized iso-paraffins (SIP) was approved by ASTM in 2014. The SIP process utilizes a fermentation process to convert a sugar feedstock into a hydrocarbon molecule [40].

TABLE II. ALTERNATIVE AVIATION FUEL PRODUCTION PATHWAYS

Renewable raw materials	Intermediate treatment process	Treatment process	Alternative aviation fuels
- Carbohydrates - Lignocellulosic biomass - Lipids	- Fermentation - Thermal-catalytic or pyrolytic conversion - Gasification	- Hydro-processed esters and fatty acids - Direct sugar to hydrocarbons - Alcohol to jet - Fischer-Tropsch - Synthetic Iso-Paraffins - Catalytic hydro-thermolysis jet fuel - Hydro-processed hydrocarbons	- Carbohydrate based fuels - Lipid based fuels

Hydro-processed Hydrocarbons (HH-SPK) was approved by ASTM in 2020. HH-SPK utilize hydro-processing of bioderived hydrocarbons which comes from oils found in an algae [40].

Hydro-processed esters and fatty acids (HEFA) was approved by ASTM in 2011. In the HEFA process, lipid feedstocks such as plant or algae oils, animal fats, or waste greases such as cooking oils are deoxygenated and then hydro-processed to produce a pure hydrocarbon fuel blending component [40].

Alcohol to jet (ATJ) was approved by ASTM in 2016 using isobutanol and in 2018 using ethanol. The ATJ process utilizes dehydration, oligomerization, and hydro-processing to convert alcohol feed stocks to a pure hydrocarbon fuel [40].

Catalytic Hydro-thermolysis Jet fuel (CHJ), or hydrothermal liquefaction, is a process where clean free fatty acid oil is combined with preheated feed water and then passed to the CH reactor where a single phase is formed. Free fatty acids are cracked, isomerized, and cyclized into paraffin, isoparaffin, cycloparaffin, and aromatic compounds [40].

IV. ALTERNATIVE FUELS FOR SMALL TURBOJET ENGINES

In general, what was mentioned in the previous chapters applies also to fuels/alternative fuels for small-scale turbojet engines. However, small turbojet engines operate at much higher speeds than large-scale engines (50,000 - 100,000 rpm), thus it is necessary to test them for new types of fuels. In the following section, research on the impact of alternative fuels on small-scale turbojet engines is summarized.

In Fig. 1 [44], there is presented mass and volumetric energy density of different fuels suitable for use in aviation.

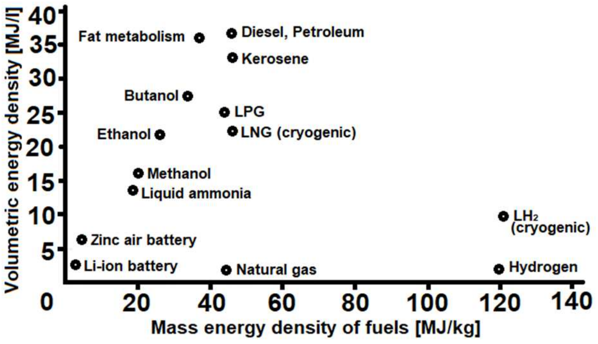

Fig. 1. Comparison of energy density of different fuels

It can be clearly seen that kerosene/gasoline/diesel have very big volumetric and average mass energy density. On the other hand, all alcohols have substantially lower energy densities. Hydrogen has by far the best mass energy density, however, its volumetric energy density is very low. It can be also seen, that energy densities of Li-ion and Zinc-air battery are very low, which makes the utilisation of "battery aircraft" not realistic with current battery chemistry [45].

A. Performance and Emission Influence of Alternative Fuels on Small-Scale Turbo-compressor Engines

Small scale turbo-compressor engines operate at much higher speed compared to common turbo-compressor engines used today on commercial aircraft. Moreover, these engines often work only for a limited period of time, but at their full power. These specifics require a detailed examination of the impact of alternative fuels on engines reliability, but also on the emission rate.

In [46], authors examined performance and exhaust emissions rate of small-scale turbojet engine running on dual biodiesel blends with JET-A fuel. Authors found that dual biodiesel blend with JET-A fuel, with ratio 10:90, gave the best specific fuel consumption value. Moreover, it produced a lower emissions rate for CO and CO$_2$ than neat JET-A fuel or other blends. NO$_x$ was for this blend close to Jet-A. Other blends exhibited worse NO$_x$ emission index.

In [47], authors investigate performance of a small-scale turbojet engine fed with: traditional JET-A fuel, a synthetic Gas to liquid (GTL) fuel and a blend of 30% Jatropha methyl ester (JME) and 70% JET-A. The GTL and JME-JET-A blend emissions showed similar behaviour of the NO$_x$ and CO, compared to the neat JET-A emissions, while the unburnt hydrocarbons were lower for the bio-fuel blend over the entire range of tested speeds (reduction 25–30%). However, blended fuels had lower heating value which caused increase engine consumption.

In [48], ten aviation alternative fuels were compared to JET-A-1 fuel and tested on small turbofan engine. Moreover, there are listed properties of these fuels as: density, viscosity, initial and final boiling point, surface tension, net heat of combustion, hydrogen content, hydrogen to carbon ratio, molecular weight, critical temperature and pressure, aromatics content, flesh point and freezing point. The paper concludes that the combustion of alternative fuels generally leads to enhancements in engine performance with respect to the use of JET-A-1 fuel (savings in fuel consumption up to 4%). Reductions in emissions occur mostly in soot, NO$_x$ and CO, depending on the fuel and operating conditions. In contrast, increased emissions of unburned hydrocarbons are generally observed.

In [49], the effect of alternative fuels on gaseous and PM emission performance was tested. Overall, eleven types of fuel were tested, namely: JET-A-1, 50% Jet A-1 and 50% SPK, 25% Jet A-1 and 75% SPK, neat SPK, diesel and 8 novel fuels. Gaseous emissions (CO, CO_2, NO, NO_x and total hydrocarbon) were similar for all tested fuels. The smoke and particulate emissions of the SPK fuel were substantially lower than other fuels.

In [50], performance and emissions of a small-scale gas turbine engine were tested for different blends of JET-A fuel (50%) with soy methyl ester, canola methyl ester, recycled rapeseed methyl ester and hog-fat biofuel. Moreover, all alternative fuels were tested without blending with JET-A fuel. Authors conclude that addition of biofuel resulted in a reduction in static thrust and fuel consumption, and increased thermal efficiency. The CO and NO emissions were reduced with the biofuel blends.

In [51], a blend of 48% synthetic hydrocarbons obtained from HEFA process with JET-A-1 were tested on miniature turbojet engine. The authors conclude that the blended fuel reduced fuel consumption and also reduced CO, CO_2 and NO_x emission.

The research [52], examines the effect on performance and environmental-economic indicators of euro diesel-hydrogen dual-fuel combustion in a small turbojet engine. Authors conclude several facts:

- the total fuel consumption decreases remarkably at each engine speed,
- specific energy consumption decreases with an increase of hydrogen energy fractions at each engine speed,
- at all engine speeds, the local gas temperature remarkably increases with an increase of hydrogen energy fractions.
- with the increase of hydrogen energy fractions at each engine speed, CO and CO_2 emissions decrease while HC and NO_x emissions increase.
- combustion efficiency increases significantly up to a 15% hydrogen energy fraction at all engine speeds, however, above this value there is no significant change in combustion efficiency.

In [53], the performance and exhaust emission of small-scale turbine engine are compared for JP-8 fuel, synthetic paraffinic kerosene fuel blends and hydro-processed renewable jet fuel blends. Results show very small difference in thrust, fuel flow and exhaust temperature for tested fuels.

In [54], the comparison of the performance and emissions produced by micro-turbine and the full-size turbofan engines, powered by blends of Jet A-1 and ATJ or HEFA produced from used cooking oil in various concentrations, are investigated. Tested fuel blends had no significant effect on engines' operating performance or fuel consumption, however, increased content of biofuels caused a noticeable rise in the emission of CO and slight increase of HC and NO_x.

In [55], authors investigate the effect of different blends of ATJ-SK with JET-A-1 fuel for PM emission. Authors conclude that burning alternative fuel blends reduces the PM emissions over the entire range of fuel flow.

In [56], performance and environmental impact of a small turbojet engine fuelled by blends of biodiesels (cotton methyl ester and corn methyl ester) are investigated for various concentrations: 10%, 20% and 50% of biodiesel in JET-A-1 fuel. The experimental results showed that biodiesel fuels can be used up to blend of 50% with JET-A-1 with slight enhancement in engine performance and significant improvements in exhaust emissions. However, the engine static thrust was for blended fuel significantly decreased at high engine speed.

In [57], authors conducted exergetic performance and exergoeconomic analyses of a small-scale turbojet engine fuelled with either conventional aviation fuel or biofuel. It is concluded that the cost rate of thrust is for the case of jet fuel 16% lower than for the case of biofuel.

V. CONCLUSION

Most of the studies testing the effect of alternative fuels on small turbo-compressor engines were carried out for blends of maximum 50% concentration of alternative fuel in conventional crude-oil based fuel. At higher percentage ratios of alternative fuels, the operational properties of the engines deteriorated. Although some alternative fuels have shown in many studies a slight improvement in engine performance at low and medium speeds, but a significant reduction in performance at high speeds. As for emissions, most studies have shown their slight reduction.

Although alternative fuels do not provide a significant decrease in emissions, or they do not have a great impact on the performance characteristics of turbo-compressor aircraft engines, their use will be necessary due to the decreasing world's crude-oil reserves.

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