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NEW TECHNOLOGIES IN COMBUSTION CHAMBERS OF AIRCRAFT TURBINE ENGINES

Nowe technologie w komorach spalania lotniczych silników turbinowych

Abstract*: The paper presents the projected emissions of combustion components over the next few years. The basic tasks that a modern combustion chamber must fulfill were defined. The process of hydrocarbon combustion in the theoretical and actual cases was analyzed. The assessment evaluates the effect of engine operating parameters such as rotational speed, thrust, temperature downstream the compressor and combustion on the formation of toxic combustion components. The paper also presents alternative fuels, i.a. sustainable aviation fuels - SAF. Alternative methods of powering aircraft engines, such as hydrogen or nuclear propulsion, were presented. An analysis on the latest combustion chamber design systems that allow to reduce the amount of exhaust gasses emitted into the atmosphere was conducted.*
Keywords: combustion chamber, aircraft turbine engine, exhaust emissions

Streszczenie: *W artykule przedstawiono przewidywane emisje składników spalania na przestrzeni najbliższych lat. Określono podstawowe zadania, jakie musi spełniać współczesna komora spalania. Przeanalizowano proces spalania węglowodorów w przypadku teoretycznym oraz rzeczywistym. Dokonano oceny wpływu parametrów eksploatacyjnych silnika, takich jak prędkość obrotowa, ciąg, temperatura za sprężarką i temperatura spalania, na powstawanie toksycznych składników spalania. Przedstawiono paliwa niekonwencjonalne, m.in. zrównoważone paliwa lotnicze – SAF. Zaprezentowano alternatywne metody zasilania silników lotniczych, jakimi są wodór czy napęd jądrowy. Dokonano analizy najnowszych układów konstrukcyjnych komór spalania, dzięki którym możliwe jest zmniejszenie ilości spalin emitowanych do atmosfery.*
Słowa kluczowe: komora spalania, lotniczy silnik turbinowy, emisja spalin

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1. Introduction

Currently, airplanes are one of the most widely used means of transportation, making them a significant source of exhaust fumes [1] [2]. In order to reduce exhaust emissions, the International Civil Aviation Organization, has developed standards to address this problem in Annex 16 to the Convention on International Civil Aviation. Due to increasing air traffic, these standards are evolving and becoming more restrictive. In 2022, the European Aviation Safety Agency published an environmental report outlining projected emissions of combustion components over the next few years. According to the report, NOx emissions, depending on increased air traffic, in 2050, could reach 1,335,000 tons (Fig. 1), and CO_2 emissions as high as 245 million tons (Fig. 2). For the sake of the environment, research should be conducted on reducing the emission of toxic components from aircraft turbine engines, as well as on new technologies that can be used in designing combustion chambers.

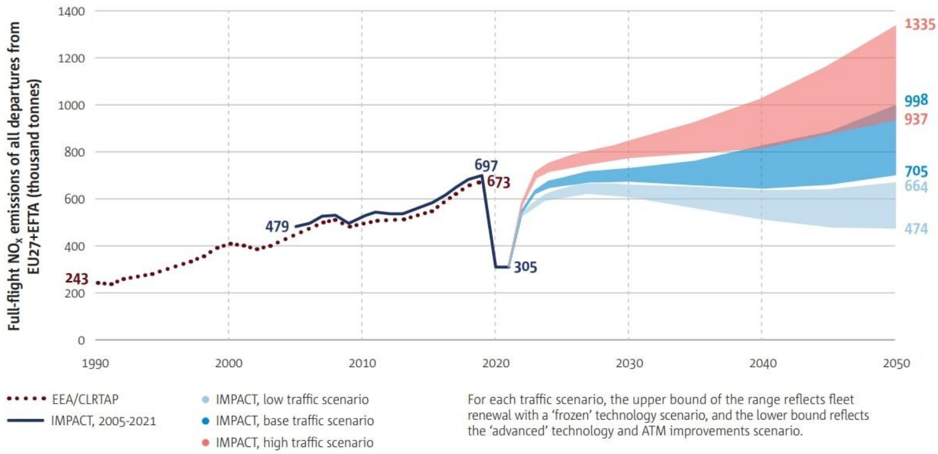


Fig. 1. Projected NOx emissions [3]

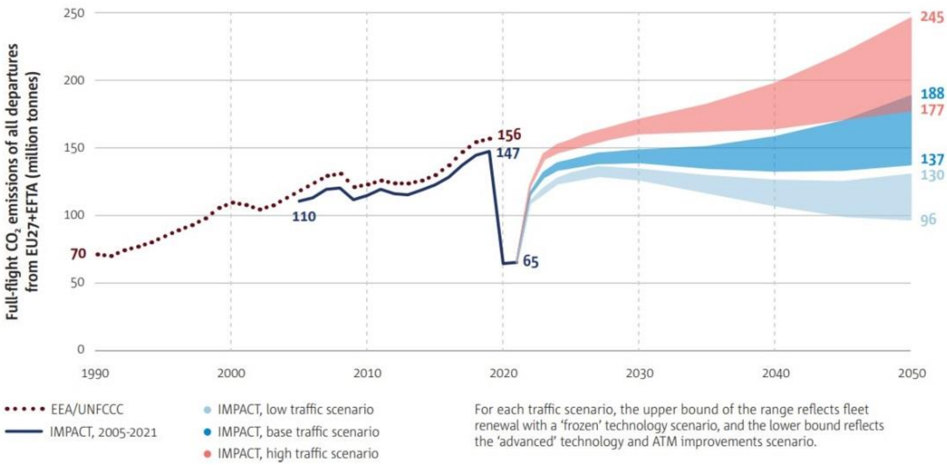


Fig. 2. Projected CO_2 emissions [3]

Knowledge in the field of exhaust emissions and their impact on the environment is presented, among others, in the monographs [4] [5] or [6]. Studies on the emission of toxic combustion components into the atmosphere and ways to reduce it are presented, for example [7] [8] and [9]. As for new technologies in the design of combustion chambers, they are described in detail in the work [10] and [11]. The issues related to hydrogen propulsion are presented in the publications [12] and [13]. In contrast, biofuels are described in [14] and [15] and electric and hybrid propulsion is described in [16].

2. Research on combustion chambers

Combustion chamber research focuses mainly on safety issues (Fig. 3a), including studies of combustion stability, ignition reliability, and engine re-start at high altitudes. Research on combustion chamber emission is also increasingly important. The combustion chamber is the only engine assembly (Fig. 4) that is responsible for converting the chemical energy contained in the fuel into mechanical energy of the increase in the velocity of the flow of combustion products and the air stream, and for producing the working medium that feeds the turbine [17]. Regarding design aspects (Fig. 3b), tubular combustion chambers, tubo-annular combustion chambers and annular combustion chambers have been produced so far. Because individual chambers do not provide a uniform circumferential temperature distribution and have a larger mass, annular chambers, which are characterized by small radial dimensions, low mass and high efficiency, are most commonly used today.

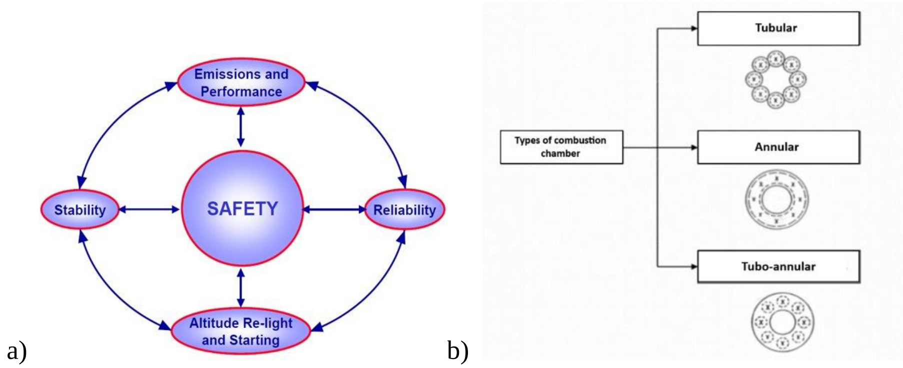


Fig. 3. Combustion chambers: a) tasks for chambers, b) types of combustion chambers

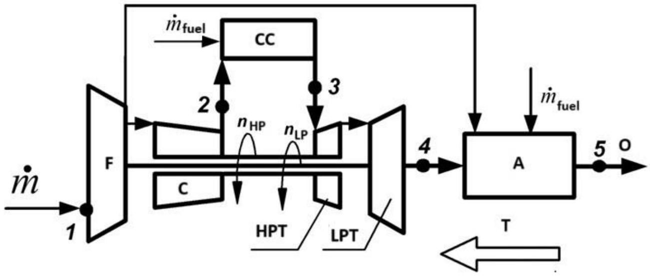


Fig. 4. Schematic diagram of a bypass turbojet engine with a mixer pass the LPT (and afterburner): F- fan; C - compressor; CC - combustion chamber; HPT – high pressure turbine; LPT - low pressure turbine; A - afterburner (mixer pass the LPT); T – thrust vector, $\dot{m}$ - airflow, $\dot{m}_{fuel}$ - fuel supply, 1, 2, 3, 4, 5 – characteristic cross sections of flow channels

When dealing with combustion chamber issues, a basic knowledge of the chemical phenomena occurring during the combustion process is essential (Fig. 5). The most used aviation fuel is kerosene, which is a mixture of hydrocarbons. The kerosene is supplied to the combustion chamber through injectors, and then forms a mixture with air which is burned. The exhaust gas mixes with the cooler secondary air and afterburning of residual fuel takes place. This process should be continuous and should ensure a uniform temperature distribution at the combustion chamber outlet. In this case we are dealing with incomplete combustion. Therefore, in addition to the "natural" combustion components, i.e., oxygen, nitrogen, carbon dioxide and water, we also get the harmful components of sulfur oxides, nitrogen oxides, or unburned hydrocarbons, and particulate matter. Nitrogen oxides, which are responsible for the destruction of the ozone layer, are particularly harmful and most action is being taken to reduce them.

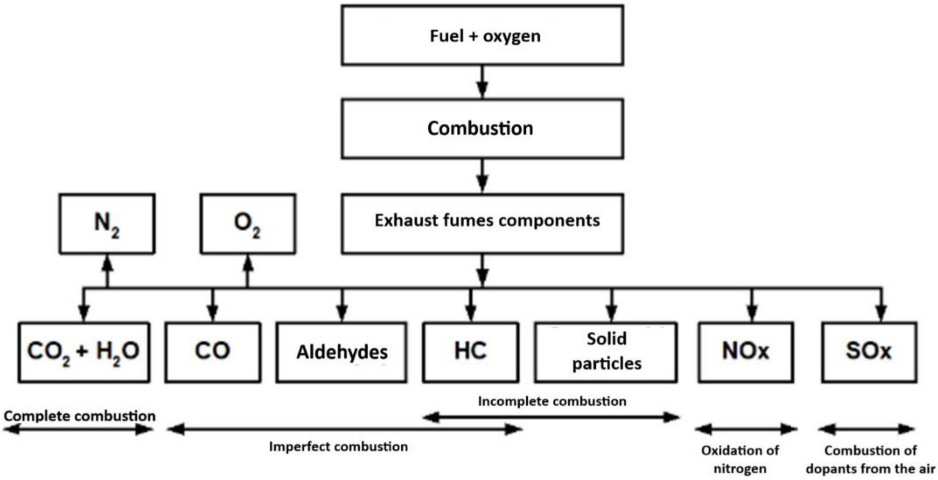


Fig. 5. Block diagram of the hydrocarbon combustion process

3. Factors affecting the formation of harmful compounds

The following formula can be used to present the perfect and complete combustion:

$$[C_nH_m + S] + [O_2 + N_2] \rightarrow CO_2 + H_2O + N_2 + O_2 + SO_2 \qquad (1)$$

Under actual conditions, the combustion process takes the following course:

$$[C_nH_m + S] + [O_2 + N_2] \rightarrow \rightarrow CO_2 + H_2O + N_2 + O_2 + SO_x + NO_x + CO + C + UHC \qquad (2)$$

where:

C_nH_m - general formula for hydrocarbons,

S - sulfur,

O_2 - oxygen,

N_2 - nitrogen,

CO_2 - carbon dioxide,

H_2O - water,

SO_x - sulfur oxides,

NO_x - nitrogen oxides,

CO - carbon monoxide,

C - soot,

UHC - unburned hydrocarbons.

Many engine operating parameters affect the formation of toxic combustion components. One of them is the rotor speed (Fig. 6a) and the associated engine thrust (Fig. 6b). According to the chart, it can be observed that an increase in both carbon monoxide and unburned hydrocarbons is evident when the engine decelerates to the idle range. This is caused by the pressure drop and, consequently, a decrease in combustion rate and not as homogeneous a mixture as required for perfect combustion. Idling, however, is the least emissive when it comes to nitrogen oxides, as temperatures are still too low at the compressor outlet. Most nitrogen oxides are formed during acceleration on the maximum range - the highest combustion temperature.

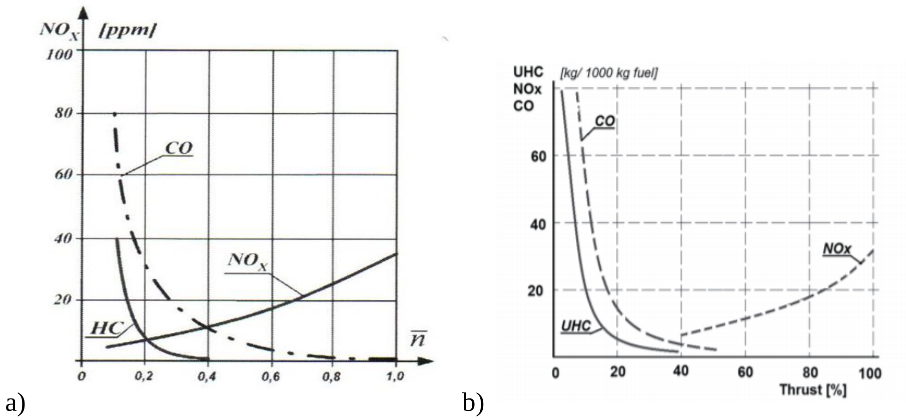


Fig. 6. Effect of engine operating parameters on toxic emissions, where: a) Effect of rotor speed on CO, HC and NO_x b) Effect of thrust on CO, HC and NO_x [17], [18]

As the combustion temperature increases, the amount of carbon monoxide and unburned hydrocarbons decreases, while the number of nitrogen oxides increases (Fig. 7). By determining these correlations, it was possible to design a new type of combustion chamber in which the combustion chamber achieves lower emissions.

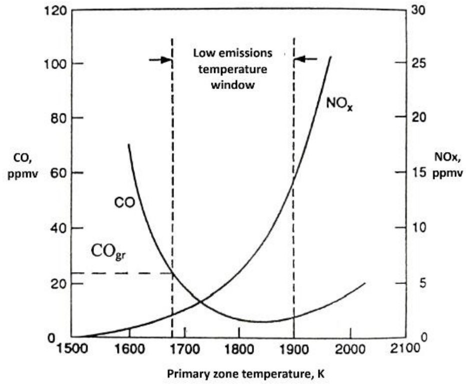


Fig. 7. Effect of combustion chamber temperature on CO and NO_x [4]

Another important parameter in this area is the temperature downstream the compressor (at the combustion chamber inlet), which is a function of engine compression. The amount of nitrogen oxides increases exponentially with an increasing temperature downstream the compressor (Fig. 8). Currently, most engines generate very high compression (e.g., the Trent 1000 engine Π*=50.0), resulting in a temperature of more than 800K which, considering exhaust emissions, turns out to be a disadvantage.

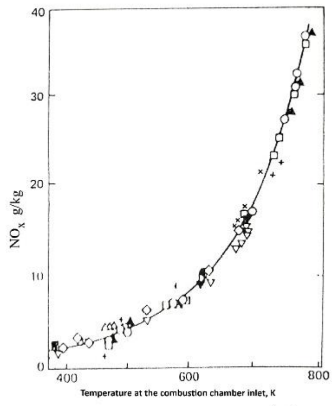


Fig. 8. Effect of temperature at the compressor outlet on emissions NO_x [4]

CO and UHC emissions can be represented as a function of air pressure at the combustion chamber inlet. Both components decrease with increasing pressure (Fig. 9).

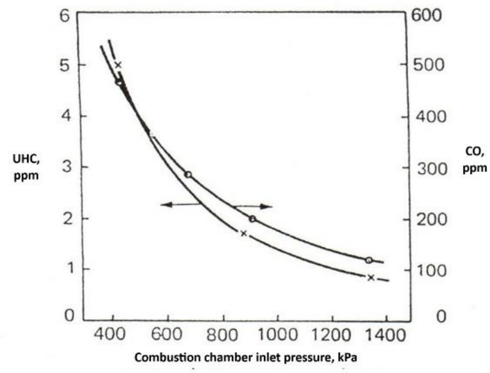


Fig. 9. Effect of chamber inlet pressure on CO and HC emissions [4]

Considering the composition of the fuel-air mixture, it can be seen (Fig. 10) that CO and HC values increase along with the excess fuel-to-air ratio increase. Emissions of NO_x reach their maximum at the stoichiometric composition of the mixture (due to the maximum combustion temperature), and then decrease as the excess fuel-to-air ratio increases. In this case, the definition of mixture composition refers to fuel, not air.

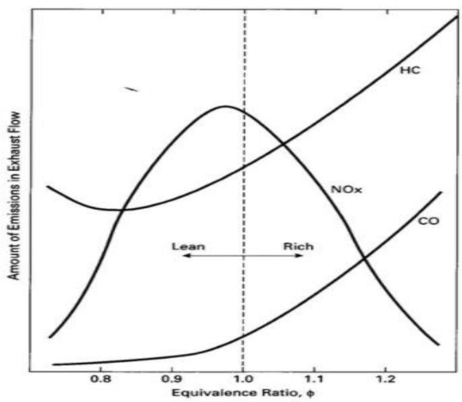


Fig. 10. Effect of excess fuel-to-air ratio on CO, HC and NO_x emissions [19]

Based on the analysis presented, it can be concluded that efforts to reduce emissions of individual combustion components contradict each other and collide with the need to achieve maximum thrust or power of an aircraft turbine engine. Therefore, optimization processes for meeting the selected criterion or criteria are important as part of the efforts on reducing exhaust emissions.

4. Alternative jet fuels

Awareness on the consequences of burning jet fuel raised the need for alternative fuels. One of the most promising aspects related to the matter is the use of sustainable aviation fuels - SAF. These fuels produce the same amount of energy as fossil fuels, however, they are produced from recycled raw materials. Vegetable fats, or animal fats (e.g., used cooking oil) can be utilized to produce biofuels (Fig. 11). The latest biofuel research seeks to use oil from plants such as jatropha, camelina, and algae. Jatropha is a plant toxic to humans and animals, undemanding in cultivation. It produces lipid oils that, although inedible, are ideal for biofuel production. Camelina is a type of hemp, which is used, for instance, in agriculture to produce animal fodder. Its main advantage is its high energy content, which can also be used to produce SAF. Algae seem to be the most promising - they are undemanding, grow quickly and provide large amounts of oil [20]. The main goal of using biofuels is to reduce carbon dioxide emissions into the atmosphere, and compared to standard jet fuel, emissions can be reduced by up to 80%.

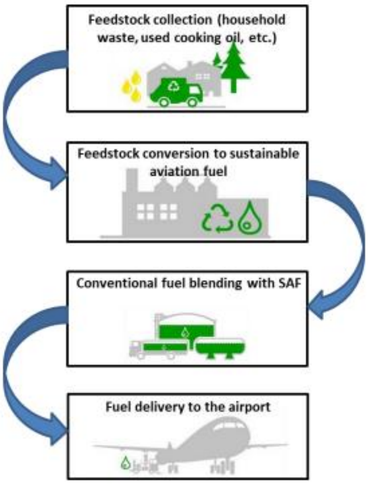
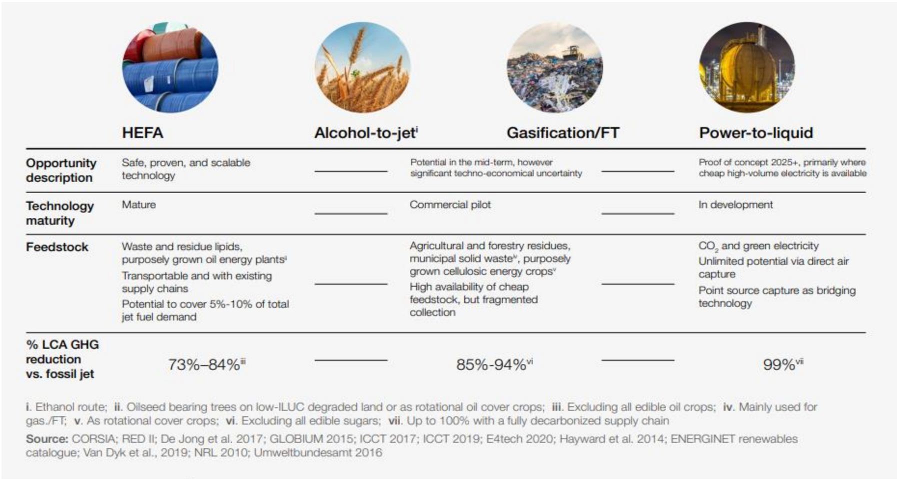


Fig. 11. The biofuel production process [14]

The most promising biofuel production technologies are shown in Fig. 12. HEFA is the processing of esters and fatty acids and is most commonly used for biofuel production. For this reason, it is a safe and most developed process. Method FT (Fischer-Tropsch) is also already in use in aviation and involves catalytic production of hydrocarbon gases from synthesis gas. The ATJ (alcohol-to-jet) process is the conversion of alcohol (ethanol) into JetA (aviation kerosene) fuel, while PTJ (power-to-liquid) involves obtaining liquid fuels from hydrogen using renewable electricity.



	HEFA	Alcohol-to-jet[i]	Gasification/FT	Power-to-liquid
Opportunity description	Safe, proven, and scalable technology	—	Potential in the mid-term, however significant techno-economical uncertainty	Proof of concept 2025+, primarily where cheap high-volume electricity is available
Technology maturity	Mature	—	Commercial pilot	In development
Feedstock	Waste and residue lipids, purposely grown oil energy plants[ii] Transportable and with existing supply chains Potential to cover 5%-10% of total jet fuel demand	—	Agricultural and forestry residues, municipal solid waste[iv], purposely grown cellulosic energy crops[v] High availability of cheap feedstock, but fragmented collection	CO_2 and green electricity Unlimited potential via direct air capture Point source capture as bridging technology
% LCA GHG reduction vs. fossil jet	73%–84%[iii]	—	85%-94%[vi]	99%[vii]

i. Ethanol route; ii. Oilseed bearing trees on low-ILUC degraded land or as rotational oil cover crops; iii. Excluding all edible oil crops; iv. Mainly used for gas./FT; v. As rotational cover crops; vi. Excluding all edible sugars; vii. Up to 100% with a fully decarbonized supply chain

Source: CORSIA; RED II; De Jong et al. 2017; GLOBIUM 2015; ICCT 2017; ICCT 2019; E4tech 2020; Hayward et al. 2014; ENERGINET renewables catalogue; Van Dyk et al., 2019; NRL 2010; Umweltbundesamt 2016

Fig. 12. Biofuel production technologies [21]

Biofuels are certainly the first, most achievable means to decarbonize aviation, however, for the time being, they are only used as an admixture to standard jet fuel. This is because aircraft need to be supplied with hydrocarbon fuel, and the biofuels currently produced are esters of higher fatty acids. However, their unquestionable advantage is that they do not require changes in airport infrastructure or in the design of turbine engine combustion chambers. Currently, the largest producers of biofuels are the Dutch Neste and the – originating from California – World Energy LLC. In Poland, Orlen produces biofuels.

In addition to biofuels, in which the combustion process is analogous to conventional fuels, it is possible to consider the use of hydrogen combustion, or the use of nuclear propulsion. In case of using hydrogen, it can be done in two ways. The first is its combustion (Fig. 13a). This process reduces the emission of harmful components into the atmosphere, however, it does not fully constitute “green energy.” The advantage of hydrogen, however, is that it has about 2.5 times the calorific value of aviation kerosene. Its second advantage is that it can be used without large interventions in changing the structure of the aircraft, as in the case of the second solution, which is the hydrogen fuel cells. Hydrogen fuel cells (Fig. 13b), in principle, work just as standard fuel cells. In this case, hydrogen is supplied to the anode, and oxygen (air) to the cathode. A catalyst at the anode decomposes hydrogen into protons and electrons, then the protons pass to the cathode through the electrolyte, and the electrons flow through an external circuit, creating the electric current. The only combustion product of such a propulsion is water [22].

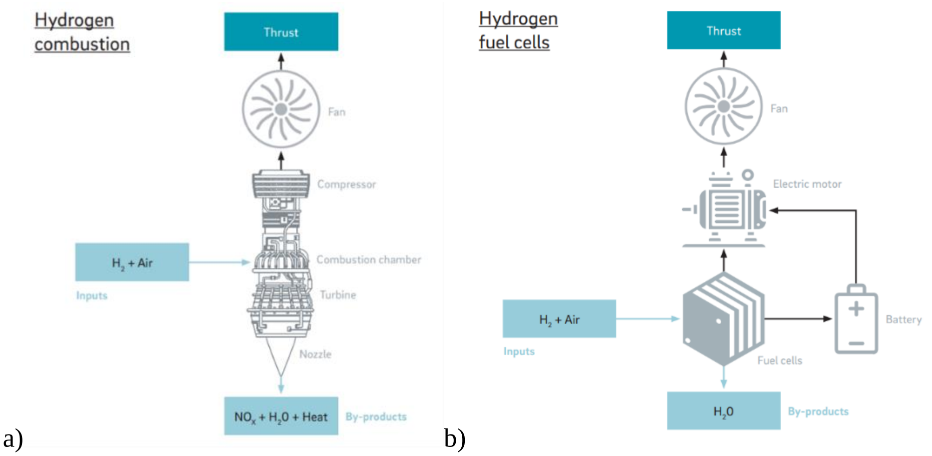


Fig. 13. Ways to use hydrogen in combustion chambers: a) hydrogen combustion, b) hydrogen fuel cells [12]

Hydrogen in Poland is currently produced from coke-oven gas during a thermochemical process. Hydrogen unfortunately is difficult to store at the airport, as well as in the aircraft's fuel tanks. The fact is that it requires significant airport infrastructure financial investment. However, this does not change the fact that hydrogen could prove to be a zero-emission aviation fuel, and with proper funding, the implementation process could be successful.

The design of hydrogen-powered engines is similar to conventional combustion engines, but modifications are necessary, particularly in the fuel supply system, such as injectors, and the organization of the combustion process.

Liquid hydrogen is a type of fuel that possesses a distinct set of properties. With a density of approximately 71 kg/m3 at its boiling point, it has a significantly lower density than traditional jet fuel, which has a density of around 800 kg/m3. As a result, it transfers only about a quarter of the energy per unit volume compared to jet fuel (34560 MJ/ m3 for Jet-A compared to 8520 MJ/m3 for LH2 with a ratio of 4.06). This means that aircraft that run on hydrogen fuel require fuel tanks that are four times larger in size than traditional jet fuel tanks, necessitating a complete redesign of the aircraft.

It should be noted that hydrogen cannot be utilized as a fuel in the existing aircraft fleet, owing to its specific storage, handling, and delivery/regasification system demands. Accordingly, it is imperative to design a new fleet of hydrogen-powered aircraft to meet these requirements.

Another attempt of using nuclear propulsion in aviation is also being considered [23]. The use of uranium is most often proposed as the element to be decomposed. This type of propulsion involves a nuclear fission reaction, which involves splitting a heavy atomic nucleus into two smaller fragments of comparable masses. The fission reaction can occur spontaneously or because of bombarding the atom nucleus with various particles (alpha, beta, etc.). In aviation, it could make sense to use nuclear batteries where no chain reaction is used, as opposed to nuclear reactors. However, the disadvantage of such a solution is the heavy weight of the battery. Currently, instead of fission reactions, the use of thermonuclear fusion based on laser systems is proposed. Such a solution was developed by Boeing, and it used a thermonuclear chamber in which many lasers of sufficient power provided radioactive material (deuterium and tritium). The radioactive material undergoes fusion reactions, and the byproducts are hydrogen and helium, providing thrust to the engine. A diagram of the engine is shown in Fig. 14.

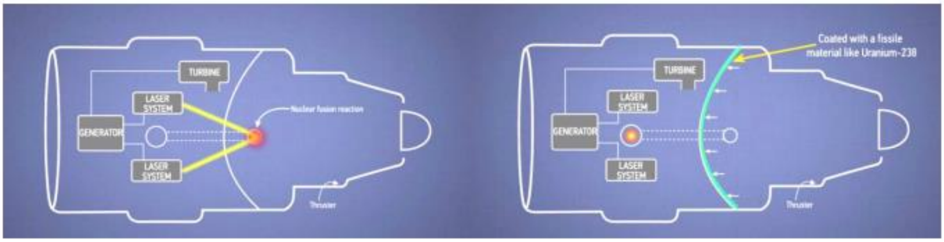


Fig. 14. Diagram of a thermonuclear chamber engine [23]

The undeniable advantage of nuclear propulsion is very low fuel consumption, so the drive could be used primarily for long-haul flights. The most important issue, however, would be to ensure safety and prevent leakage of hazardous substances into the atmosphere.

Fig. 15 shows a comparison of the discussed unconventional methods of supplying energy to aircraft engines. As already mentioned, the use of biofuels is currently the most feasible, however, biofuels have a lower potential to reduce harmful components released to the atmosphere. Other methods pose many challenges for engineers, but overcoming technological difficulties will certainly be beneficial for the natural environment.

Comparison vs fossil kerosene	(1) Battery-electric	(2) H_2 fuel cell	H_2 turbine	(3) Sustainable aviation fuel
Climate impact[i]	100% reduction[ii]	75%-90% reduction	50%–75% reduction	30%-60% reduction[iii]
Aircraft design	Low-battery density limits ranges to 500km–1,000km	Feasible only for commuter to short-range segments	Feasible for all segments except for flights >10,000km	Only minor changes
Aircraft operations	Same or shorter turnaround times	1-2x longer refuelling times for up to short range	2–3x longer refuelling times for medium and long range	Same turnaround times
Airport infrastructure	Fast-charging or battery exchange system required	LH_2 distribution and storage required		Existing infrastructure can be used

Major advantages Major challenges

i. Including CO_2, NOx, water vapour and contrails ii. Assuming 100% renewable electricity iii. For e-fuels with fully decarbonized supply chain
Source: Clean Sky 2 JU & FCH 2 JU: Hydrogen-powered aviation report (made possible with funding provided by the EU); expert interviews

Fig. 15. Comparison of alternative energy sources for aircraft propulsion [21]

5. Low-emission combustion chambers

To reduce emissions of toxic combustion components, engineers are developing new combustion chamber design systems. The leading designs today are the LPP, RQL, TAPS type chambers, as well as dual combustion chambers [10].

The LPP (Lean Premixed Prevaporized) chamber refers to a chamber (Fig. 16) in which a lean, premixed and pre-vaporized mixture is burned. The combustion chamber's flame tube is divided into three zones - the first for injectors, evaporation and mixture formation, the second for combustion and the third for cooling. LPP is one of the most promising methods for reducing NOx emissions.

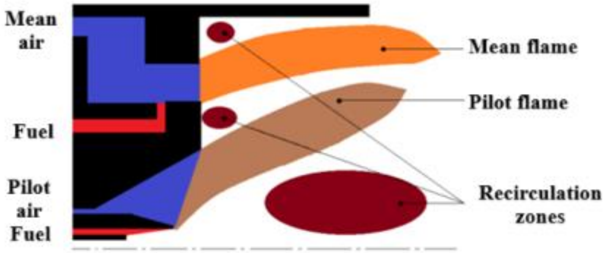


Fig. 16. LLP type chamber [11]

RQL (Rich-burn Quick-quench Lean-burn) chambers, on the other hand, burn a rich mixture (Fig. 17), making the combustion process stable and reducing NOx emissions. Unfortunately, high emissions of carbon monoxide and unburned hydrocarbons are typical for this chamber. A chamber of this type was used by Pratt & Whitney under the name TALON X.

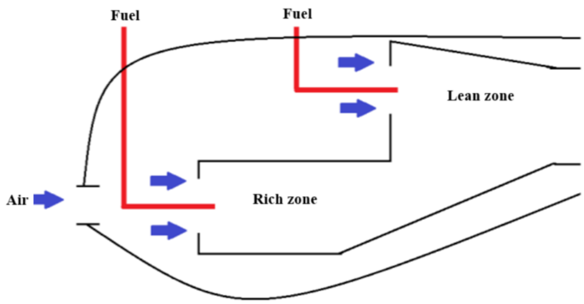


Fig. 17. RQL type chamber [11]

In the TAPS (Twin Annular Premixing Swirler) chambers, (Fig. 18), NOx emissions are reduced due to pre-mixing of the mixture, and an even temperature field distribution at the turbine inlet is also ensured.

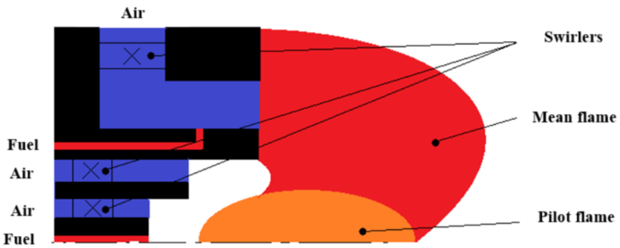


Fig. 18. TAPS type chamber [11]

With dual chambers (VORBIX), the combustion process is divided between two zones (Fig. 19). The first operates on the idle range to reduce CO and UHC emissions, while the second (main) operates on the maximum range and reduces NOx emissions. Air and fuel are supplied through appropriately placed swirlers.

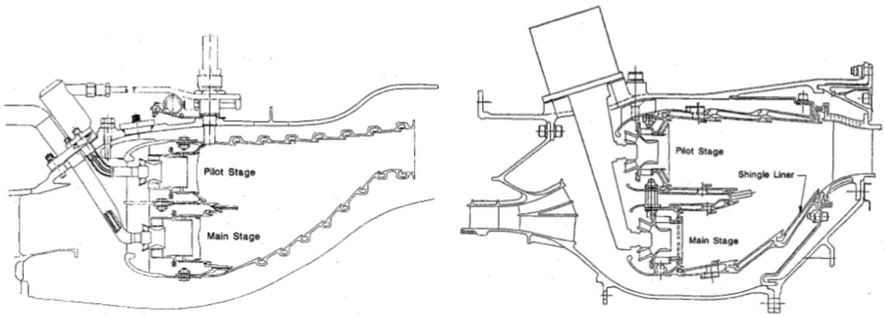


Fig. 19. VORBIX type chamber [24]

6. Conclusions

Contemporary research must focus on developing new designs that can meet current and future imposed environmental standards for reducing toxic emissions. Research and development are focused on a few selected areas. In new combustion chamber designs, these areas primarily include changes to the fuel and its supply method, which can lead to lower emissions of nitrogen oxides, carbon monoxide and unburned hydrocarbons. Another area is a combustion chamber design layout change and reorganizing the combustion process. Any new combustion chamber designs that are developed advance knowledge about ways to reduce emissions and have a positive impact on improving the atmosphere. Each of the technologies presented in the paper can provide reductions in emissions of toxic components. While in the case of biofuels we can already see the effects, in the case of hydrogen fuel cells or the use of nuclear propulsion the work is just beginning to take its proper form. The use of hydrogen combustion may be the proper direction with great development potential in the field of aircraft propulsion systems. In the case of the use of nuclear energy, it is an opportunity to achieve zero emissions and research should also be carried out in this area.

Acknowledgements
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