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THE EFFECT OF TOXIC AND HARMFUL EMISSIONS OF EXHAUST GASES FROM AVIATION ENGINES ON THE ENVIRONMENT

Summary. The rapid growth of aviation makes a realistic assessment of harmful emissions crucial. The growing demand for air transportation is leading to an increase in aircraft production, which significantly affects the environment. The priority of modern aviation technology is to reduce noise, fuel consumption and exhaust emissions, especially carbon dioxide and particulate matter. Modern research is focused on finding environmentally friendly solutions to reduce the negative effects of aircraft operation. The introduction of modern technologies and more efficient combustion systems is key to the sustainability of air transport and environmental protection.

Key words: aviation engines, exhaust gases, harmful emissions, toxic emissions, aircraft engines.

Statement of the problem. The biggest challenge is to reduce emissions of nitrogen oxides (NOx), sulfur oxides (SOx), carbon monoxide (CO) and unburned hydrocarbons (HC) [1, 2]. Their presence in the atmosphere contributes to smog, acid rain and increases in tropospheric ozone concentrations [3]. The engines of passenger and transport aircraft generate the most pollution because they consume huge amounts of fuel relative to the thrust achieved. Long-haul flights taking place at an altitude of 8–12 km, where the highest concentrations of toxic compounds are observed, have a particularly significant impact on the environment. At lower altitudes, up to 1 km, only 5–10% of the world's aviation fuel is consumed, but it is in the areas around airports that air pollution has a direct impact on human health.

Although aviation accounts for about 2% of global greenhouse gas emissions, its impact on air quality and human health is significant, especially in regions with heavy air traffic [4]. Global emissions from the sector increased by more than 75% between 1990 and 2012, and projections indicate that they could increase 2 to 7 times by 2050, accounting for up to 20% of global emissions [1]. Further efforts are therefore needed to reduce aviation's negative impact on the environment.

The future of aviation involves research into electric and hybrid propulsion systems, which can significantly reduce emissions [5–7]. At the same time, CAEP standards regulate engine emissions, but the problem of exhaust toxicity affects not only high altitudes, but also areas around airports, where it affects the quality of life of local communities.

Analysis of recent research. Reducing environmental impact is a key goal of modern aviation technology. As a rapidly developing field, transportation is subject to constant improvements, including both the modernization of existing machinery and the implementation of new emission-reducing designs. Aviation, growing at a rapid pace, competes with road transport as a major transportation industry. In more than a century of existence, the industry has undergone numerous changes and continues to evolve. In Poland, environmental deterioration can be linked to the increase in aircraft use. Exhaust emissions regulations focus mainly on passenger and transport aircraft, which are responsible for the largest toxic emissions into the atmosphere. Carbon monoxide and carbon dioxide have a key impact on the environment, contributing to the greenhouse effect and permanent climate change.

Task statement. The introduction of modern technologies and more efficient combustion systems for sustainability of air transport and environmental protection.

The main part. Studies of toxic emissions in aviation focus mainly on turbine engines. Modern jet engine development seeks to maximize thrust, minimize fuel consumption and optimize exhaust emissions [8]. The efficiency of these engines has always been a key concern for designers, affecting the range and payload of aircraft [9].

We divide the combustion products from aviation turbine engines into:

- natural products of combustion such as: carbon dioxide, water, nitrogen oxides;
- incomplete combustion products: carbon monoxide, hydrocarbons, soot;
- products related to fuel quality: sulfides and metals [10].

The approximate values of the compounds from burning 1 kg of aviation kerosene in 3.4 kg of oxygen are presented in the following Table 1 [10]:

Table 1

Values of compounds from burning 1 kg of kerosene in 3.4 kg of oxygen [10]

3,16 kg	CO_2
1,29 kg	H_2O
< 0,6 g	CO
< 15 g	NO_x
< 0,8 g	SO_2
< 0,01 g	CH
< 0,03 g	C

The table shows that the main products of combustion are carbon dioxide (58% of the exhaust mass) and water vapor (41% of the exhaust mass). The largest power units, used in passenger and transport aircraft, emit pollutants at an altitude of about 10 km [1]. According to the source [11], between 5 and 15% of global fuel consumption is attributable to flights up to 1 km above sea level. Aviation kerosene has a heating value of about 43 MJ, a low freezing point and a cetane number that facilitates engine starting [1].

The products of combustion contribute to adverse phenomena such as acid rain, increased ozone concentrations and smog. An important issue is estimating the environmental impact of air transportation due to the continued growth of air traffic. Research is currently being conducted on the implementation of electric aircraft propulsion, which will result in significantly lower emissions in the future [12, 13]. However, it should be remembered that the average lifetime of an aircraft is 15–20 years.

In the international aspect, between 1990 and 2014, the number of flights increased by 80% [8]. Accordingly, carbon dioxide emissions increased from 88 million tons to 156 million tons between 1990 and 2005 [14]. For nitrogen oxides, the increase in emissions during these years was from 316,000 tons to 516,000 tons. According to estimates [14], nitrogen oxides emissions will double by 2035, reaching 920,000 tons. Emission projections over 20 years are shown in the table below (Table 2).

Table 2

Emissions of flue gas over a 20-year period [14]

	2005	2014 (Percent change from 2005)	Forecast in 2035 Advanced technology – existing technology (percentage change from 2005)
Average fuel burned per passenger-kilometer [kg]	0.0388	0.0314 (–19%)	0.0209–0.0222 (–46%) (–43%)
CO_2 [Mt]	144	151 (+5%)	207–219 (+44%) (+53%)
NOx [kt]	650	732 (+13%)	920–1049 (+42%) (+61%)
NOx under 1 km [kt]	53.3	58.8 (+10%)	73.3–83.1 (+37%) (+56%)
HC [kt]	20.8	17.0 (–18%)	22.9 (+10%)
HC under 1 km [kt]	7.8	6.4 (–18%)	11.0 (+40%)
CO [kt]	143	133 (–7%)	206 (+44%)
CO under 1 km [kt]	52.4	48.2 (–8%)	85.5 (+63%)
PM 2,5 [kt]	4.18	4.47 (+7%)	6.93 (+66%)
PM 2,5 under 1 km [kt]	0.27	0.27 (–1%)	0.41 (+50%)
PM 10 [kt]	2.67	2.38 (–11%)	3.16 (+18%)
PM 10 under 1km [kt]	0.15	0.13 (–14%)	0.17 (+11%)

Although the aviation industry is responsible for 2% of greenhouse gas emissions, the problem should not be underestimated, as deterioration of air quality affects both the environment and human health. Approximately five thousand premature deaths are recorded annually among residents of areas around airports due to particulate emissions [15, 16].

Unlike road transport, where internal combustion engines meet EURO standards, aircraft engine emissions are classified by the CAEP standard.

The development of the LTO acronym comes from the Landing/Take OFF cycle. The LTO cycle (Fig. 1) includes the various phases of flight [10]:

- Take-off – thrust setting 100%; time about 1 min,
- Climbing – thrust setting 85%; time about 2 min,
- Approach to landing – thrust setting 30%; time about 4 min,
- Taxiing – thrust setting of 7%; time approx. 26 min.

The LTO cycle focuses on measuring aircraft emissions. Tests should be conducted at specific thrust levels and durations. It is crucial that the test conditions correspond to the International Standard Atmosphere (ISA).

The jet engine's operating parameters change in proportion to the thrust setting. The LTO cycle includes measurements up to one kilometer above airport level.

Exhaust emissions are tested by placing a measuring probe in the stream of escaping gases. An example of a mobile exhaust gas analyzer is Semtech-DS, which measures the concentration of carbon dioxide, carbon monoxide, hydrocarbons and nitrogen oxides. An example photo of the analyzer is shown below (Fig. 2).

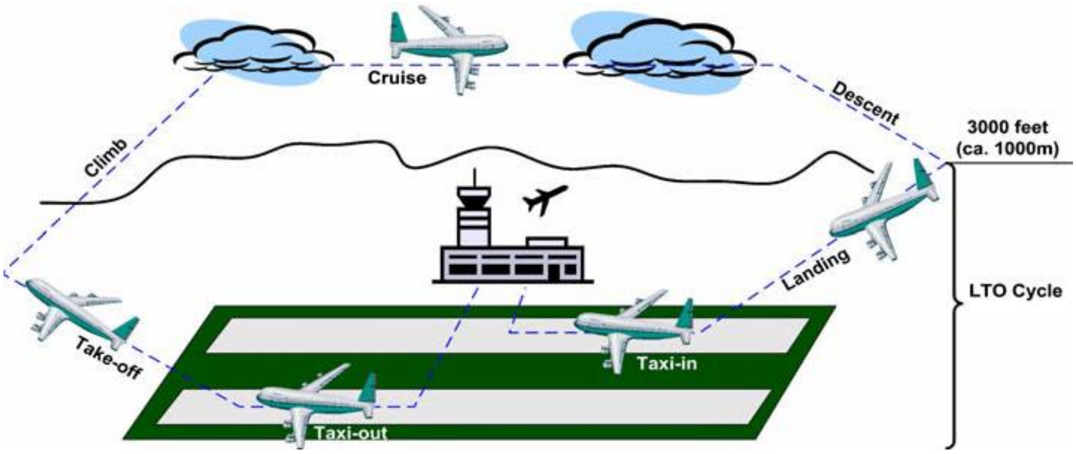

Fig. 1. LTO cycle [18]

Fig. 2. Overview photo of Semtech analyzer

Due to the limited possibilities of mounting the apparatus on the aircraft, the tests are carried out stationary on the tarmac. The analyzer (Fig. 3) additionally allows measurement of the exhaust flow rate.

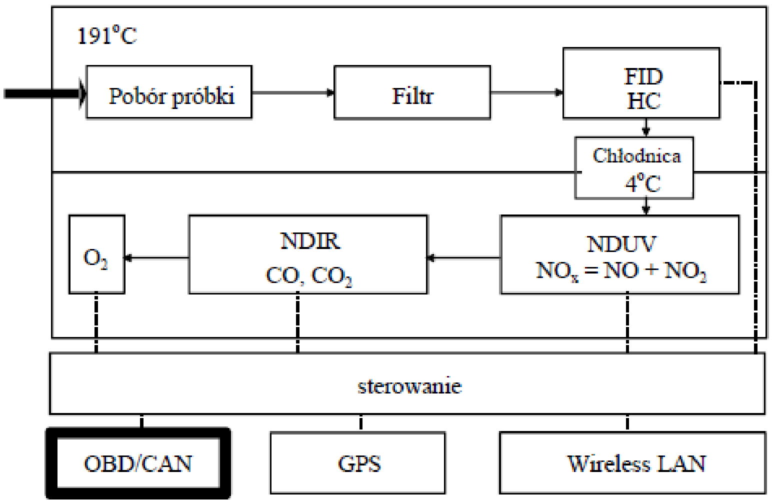

Fig. 3. Schematic of the exhaust gas analyzer [15]

A comparative analysis of carbon dioxide emissions was conducted on the engines of two types of aircraft: Boeing 737–800 and Airbus A320. For this purpose, an emission calculator was used [10] for the Warsaw-London route. The emission calculator makes it possible to determine how large the carbon footprint is, i.e. carbon dioxide emissions per passenger. This footprint will, of course, depend on how full the plane is with passengers. Our designated route is 1475 km and takes an average of 2h and 20 min, while the plane is filled to 100% capacity. The chart below shows a comparison of carbon dioxide emissions for two types of aircraft (Fig. 4).

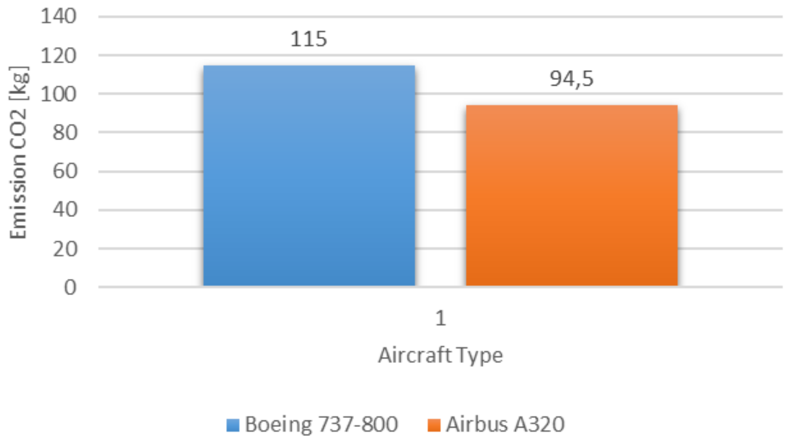

Fig. 4. Comparison of carbon emissions on the Warsaw-London route

For the same number of passengers, carbon dioxide emissions on the Warsaw-London route for a Boeing 737–800 aircraft were 115 kg, while for an Airbus A320 aircraft they were 94.5 kg.

Toxic compounds include carbon monoxide, hydrocarbons, and nitrogen and sulfur oxides [17]. The emissions of these substances can be determined mathematically, but the values obtained are for ideal ISA conditions [18]. Based on the author's research [1], the emission factors of CFM56 (Airbus A320) and Pratt & Whitney JT8D engines are presented for carbon monoxide (Table 3), nitrogen oxides (Table 4) and hydrocarbons Table 5) in the LTO cycle.

Table 3

LTO cycle carbon monoxide emissions for Boeing 737 and Airbus A320 engines

Engine	CO_{START} [g/kg]	CO_{CLIMB} [g/kg]	$CO_{APPROACH}$ [g/kg]	CO_{IDLE} [g/kg]	Dp/Foo dla CO [g/kN]
CFM56-7B26/3	0.25	0.16	3.07	30.94	46.81
PW JT8D	1.2	1.9	9.4	35.0	134.7

The data presented shows that during idling, carbon monoxide emissions into the atmosphere increase significantly.

Table 4

LTO cycle nitrogen oxide emissions for Boeing 737 and Airbus A320 engines

Engine	NOX_{START} [g/kg]	NOX_{CLIMB} [g/kg]	$NOX_{APPROACH}$ [g/kg]	NOX_{IDLE} [g/kg]	Dp/Foo dla NOX [g/kN]
CFM56-7B26/3	21.79	17.8	8.93	4.27	40.71
PW JT8D	18.9	14.6	5.8	2.75	56.1

Observing the data in Table 4, we note that for takeoff and climb, nitrogen oxide emissivity is the highest. This is the opposite phenomenon to carbon monoxide emissions [18].

Table 5

LTO cycle hydrocarbon emissions for Boeing 737 and Airbus A320 engines

Engine	HC_{START} [g/kg]	HC_{CLIMB} [g/kg]	$HC_{APPROACH}$ [g/kg]	HC_{IDLE} [g/kg]	Dp/Foo dla HC [g/kN]
CFM56-7B26/3	0.02	0.02	0.05	1.75	2.58
PW JT8D	0.4	0.45	1.4	10.0	36.8

The hydrocarbon content of the exhaust gas is lowest for takeoff and climb. For idling, these values are already dozens of times higher [9].

Based on the tables shown, it can be concluded that as engine thrust increases, carbon monoxide and hydrocarbon emissions decrease, while nitrogen oxides increase. This is due to the higher combustion temperature at higher engine power, which promotes the combustion of these compounds [19].

The toxic content was also evaluated for two types of engines: Pratt & Whitney JT8D and CFM56 on the Warsaw-London route (Fig. 5, Fig. 6).

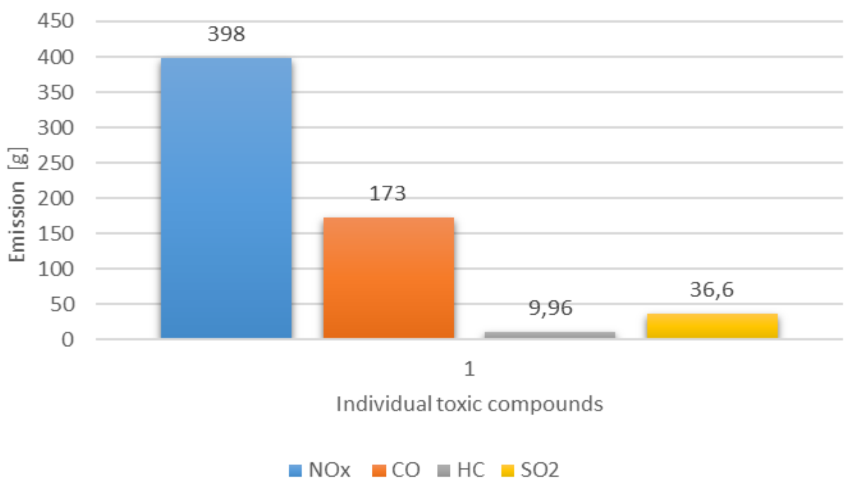

Fig. 5. Toxic emissions on the Warsaw-London route for a Boeing 737 aircraft

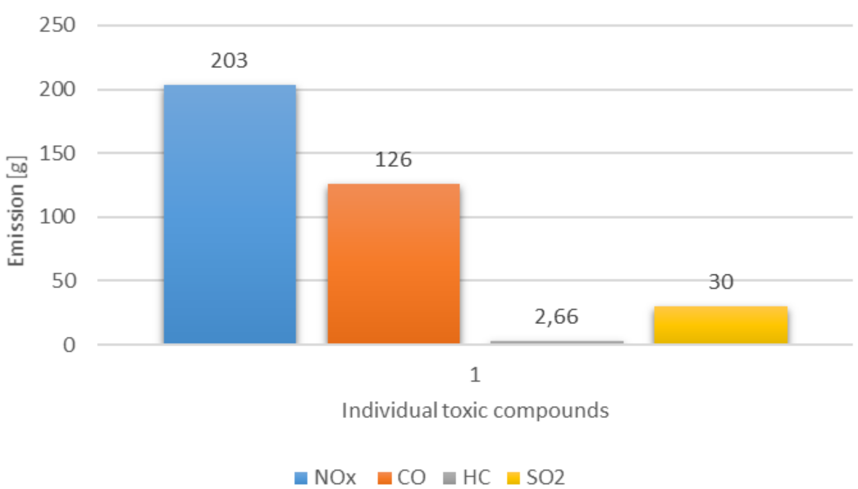

Fig. 6. Toxic emissions on the Warsaw-London route for an Airbus A320 aircraft

All toxic emissions values are lower for the Airbus A320 engine. However, it should be noted that the thrust of the CFM56 engine is almost 10 kN less than that of the Boeing engine [20, 21]. Water vapor was omitted from the comparative analysis because it is not a toxic compound [22, 23]. For Boeing 737–800 engines, the water vapor emission on the set route is 45 kg, while for Airbus A320 engines it is 37 kg [24–26].

Conclusions. According to forecasts, the increase in air traffic will continue for decades to come. In 2019, the number of passengers served at Warsaw-Okecie Airport was 18,844,591, an increase of 6.2% compared to 2018. Therefore, it is worth considering the impact of aircraft emissions on human health and the environment. The problem is not just emissions at cruising altitudes, but also at airports. Some airlines report on their websites the amount of carbon dioxide emitted per passenger on a particular flight. This gas contributes to the greenhouse effect. Per statistical inhabitant of our planet, the average carbon dioxide emission is 4.5 tons. For comparison, such a standard per passenger is realized by a seven-flight from Warsaw to Chicago.

Improvements in aircraft engines, based on changes in combustion chambers and raising exhaust gas temperatures, result in decreases in carbon monoxide and hydrocarbon emissions. Through comparative analysis for engines : Pratt & Whitney JT8D (Boeing 737–800) and CFM56 (Airbus A320), it can be concluded that during takeoff and climb, the values of carbon monoxide and hydrocarbons are negligible. It is during taxiing and parking that CO and HC values will be highest. For nitrogen oxides, the relationship is the opposite, i.e., as the exhaust gas temperature increases, there is a higher emission value. To accurately manage the emissions of compounds contained in the exhaust gas, it is necessary to have a thorough understanding of the flow and thermal processes taking place inside the combustion chamber.

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ВПЛИВ ТОКСИЧНИХ ТА ШКІДЛИВИХ ВИКИДІВ ВИХЛОПНИХ ГАЗІВ АВІАЦІЙНИХ ДВИГУНІВ НА НАВКОЛИШНЄ СЕРЕДОВИЩЕ

Анотація

Швидке зростання авіації робить реалістичну оцінку шкідливих викидів вирішальною. Зростаючий попит на авіаперевезення призводить до збільшення виробництва літаків, що значно впливає на навколишнє середовище. Пріоритетом сучасних авіаційних технологій є зниження шуму, споживання палива й викидів вихлопних газів, особливо вуглекислого газу та твердих часток. Сучасні дослідження спрямовані на пошук екологічно чистих рішень для зменшення негативних наслідків експлуатації літаків. Найбільшою проблемою є скорочення викидів оксидів азоту (NOx), оксидів сірки (SOx), оксиду вуглецю (CO) і незгорілих вуглеводнів (HC). Їх присутність в атмосфері сприяє утворенню смогу, кислотних дощів і збільшення концентрації озону в тропосфері. Найбільше забруднюють двигуни пасажирських і транспортних літаків, оскільки вони споживають величезну кількість палива порівняно з досягнутою тягою. Особливо значний вплив на навколишнє середовище мають далекі перельоти, що здійснюються на висоті 8–12 км, де спостерігаються найвищі концентрації токсичних сполук. На менших висотах, до 1 км, споживається лише 5–10 % світового авіаційного палива, але саме в районах навколо аеропортів забруднення повітря безпосередньо впливає на здоров'я людини. Хоча на авіацію припадає близько 2 % світових викидів парникових газів, її вплив на якість повітря та здоров'я людей є значним, особливо в регіонах з інтенсивним повітряним рухом. Глобальні викиди в цьому секторі зросли більш ніж на 75 % між 1990 і 2012 роками, і прогнози вказують на те, що вони можуть зрости у 2–7 разів до 2050 року, становлячи до 20 % глобальних викидів. Тому потрібні подальші зусилля для зменшення негативного впливу авіації на навколишнє середовище. Упровадження сучасних технологій і більш ефективних систем спалювання є ключовим фактором стійкості повітряного транспорту та захисту навколишнього середовища.

Ключові слова: авіаційні двигуни, вихлопні гази, шкідливі викиди, токсичні викиди, авіадвигуни.