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AVIATION – ENVIRONMENTAL THREATS

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Abstract

Based on the available information and authors self-assessments, this article presents turbine engine exhaust gases effect on the environment, especially near to the aircraft and helicopters during their engines idle setting and take-offs.

The concentration level of pollutants in gas turbine exhaust and its relation to the temperature and time of the combustion process is discussed. The article presents diffusion of the aircraft turbine engine exhaust in the airport area, focusing on aircraft take-off manoeuvre. The authors would like to draw attention of the aviation professionals to the fact that amount of exhaust from the turbine engine is so significant that may adversely change the ambient air near to the aircraft. Consequently, smaller amount of oxygen with increased level of carbon monoxide during engine start –up and idle can be a threat to the maintenance staff health. Also high emission level of the nitrogen oxides, especially during take-off and climb is indifferent for the environment.

The paper gives an example of real fuel consumption and toxic gases emissions in the so-called landing and take-off cycle (LTO) and during long-range flight.

Turbine engines noise distribution and its intensity because of complex aerodynamic and thermodynamic processes is presented.

Keywords: *turbine engine, exhaust gases, pollutant, ecology, environment, engine noise*

1. Introduction

According to statistical data, fossil liquid fuels "consumed" by modern aviation reach approx. 3% of total used by mankind [2]. Seemingly, this is a negligible quantity, but the production and dispersion of the exhaust gases emitted into the atmosphere takes place in a particularly undesirable way, i.e. in one point (airport), during taxiing and aircraft take offs and landings. Engine exhausts are also spreading during flights at high altitudes (over 10,000 meters) with speed close to 1000 km/h.

Contribution of military aviation to environment pollution in comparison with the commercial is small but noticeable due to inconvenience to the maintenance staff of combat aircraft, helicopters and residents of surrounding airports houses.

It is a cliché that exhaust gas from jet engines and exhaust gas plus air from turbofan engines has negative impact on the environment. But we have to know that mass flow of the exhaust gases currently varies between 20 kg/s and 180 kg/s and air flow rate in turbofan engines exceeds 1300 kg/s. Air velocity in the inlet (Fig. 1) is around 200 m/s and 300 m/s behind fan, while engine exhaust speed is 500 m/s and in the case of engines with afterburner even 900 m/s.

These huge masses of "pumped" air and exhaust gases discharged into the atmosphere at high speeds are a source of enormous noise.

Carbon dioxide (CO_2) pollution as well as toxins: carbon monoxide (CO), unburned hydrocarbons (UHC) and particularly nitrogen oxides (NO_x) are not indifferent to humans and animals. NO_x are dangerous and its effect on the ionosphere has not been fully explored yet (after all it is emitted during flights on high altitudes).

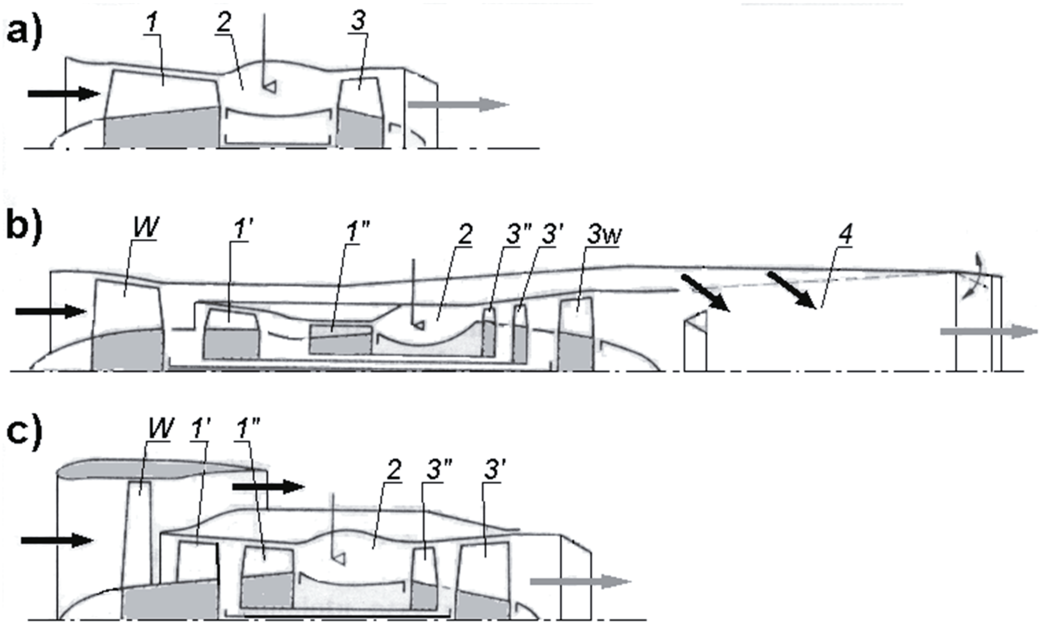

Fig. 1. Turbine engines flow diagrams: a) single rotor, b) turbofan with afterburner, c) turbofan : 1, 1', 1" – compressors, 2 – combustion chamber, 3, 3', 3" – turbines ; 4 – afterburner, W – fan

2. Engine noise

Turbine engine ducts, through which air flows and hot gases, are extremely aerodynamically complex. Stream of air flowing through the compressor and hot gases flowing through the turbine are highly shredded by vanes and rotor blades (rotating with circumferential speed of several hundred meters per second). Features of the gases flowing through the engine ducts are extremely dynamic in means of pressure, temperature, speed and density. Hence, it is easy to state that different frequencies and amplitudes are occurring when these parameters have changed. The intensity of these phenomena depends on the rotors speed, altitude and aircraft air speed because air density and air mass flow are changing.

Figure 2 shows the distribution of noise intensity generated by jet engines: single shaft with afterburner and turbofan, both with similar mass flow rates through the core duct.

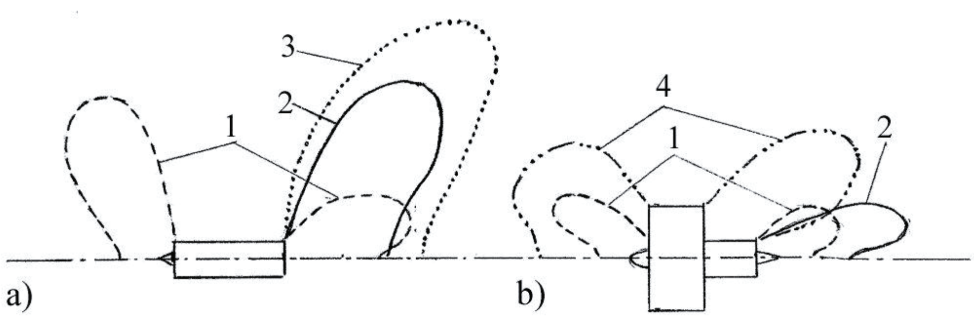

Fig. 2. Distribution lines of equal noise intensity in the immediate vicinity of jet engines: a) single shaft with afterburner, b) turbofan. Sources of noise: 1 – compressor, 2 – exhaust, 3 – exhaust with afterburner, 4 – fan

The distributions of noise is indicated as lines of constant (and the same for both engines) intensity closely to the engines. For both dominant is a noise element formed as a result of the gases outflow from the engine exhaust nozzle and – of course – reaching max. intensity during afterburner usage.

Limitation of the turbofans noise is achieved by adopting adequate aerodynamic profiles of the fan blades air foils and fan pressure ratio reduction.

3. Engine exhaust gases toxic compounds emission

During the movement of the aircraft on the airport using their own engines (working at close ranges to idle) there is the phenomenon of the fuel incomplete combustion hence exhaust from an aircraft gas turbine is composed of high amount of carbon monoxide (CO) and unburned hydrocarbons (UHC). Opposite, at the maximum thrust ranges due to high temperatures in the combustion zone -significant amounts of undesirable, highly toxic nitrogen oxides NO_x are formed. Differentiation of these components composition is a result of the air-fuel mixture changes in combustion zone as a function of engine power setting in a different climatic and aircraft flight conditions.

Listed in Fig. 3 plots of the nitrogen oxides (NO_x) content in the gas turbine exhaust, depending on the fuel - air mixture composition λ (the fuel-air equivalence ratio of a system is defined as the ratio of the fuel-to-oxidizer ratio to the stoichiometric fuel-to-oxidizer ratio) and nitrogen oxides (NO_x), carbon monoxide (CO) depending on the combustion temperature are reflecting effects of the mass fuel flow adjustment to the current air mass flow (at different engine subassemblies efficiencies)not only resulting from engine power level but also flight conditions.

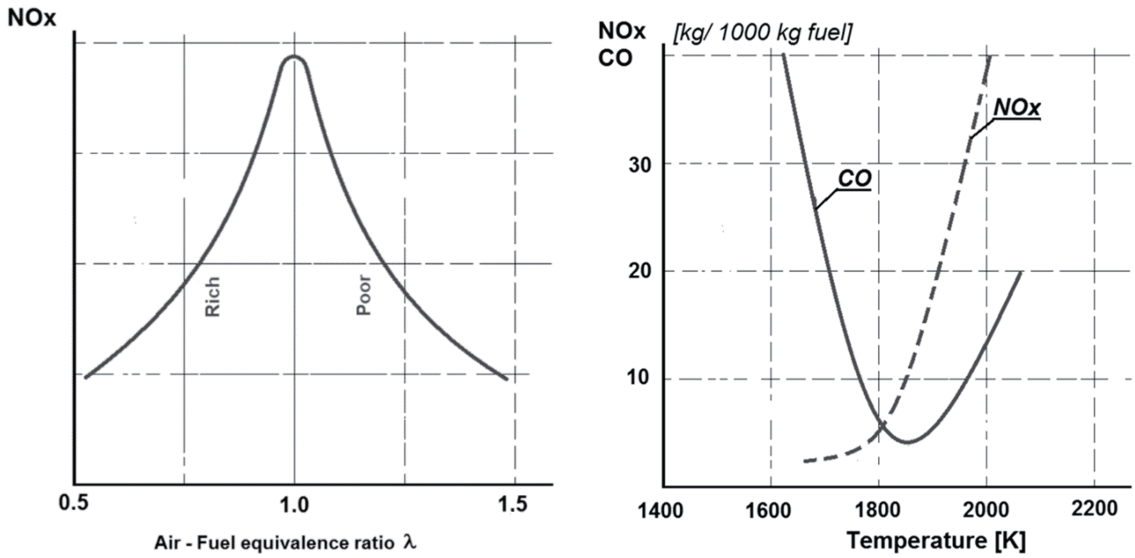

Fig. 3. Influence of equivalence ratio on NO_x emission and influence of combustion temperature on CO and NO_x emission (based on [3])

For aircraft “users” more useful is a practical knowledge how quantitative content of UHC, CO and NOx emissions depend on current engine thrust.

Figure 4 shows typical for modern jet engines used by passenger and cargo aviation exhaust emission characteristics. It is clear that the nature of toxic exhaust gases components formation is such that the concentration of CO and UHC are highest at low engine power conditions and diminish with an increase in power.

From the other hand NO_x, formation is insignificant at low power settings and reaches maximum value at highest power condition.

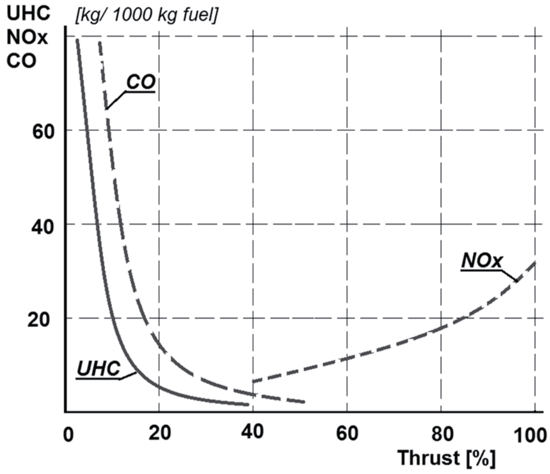

Fig. 4. Emission characteristics of gas turbine engine (based on [3])

The parameters of the maximum power of the engine with high combustion temperatures diminish emission of UHC and CO, but unfortunately – favour the formation of nitrogen oxides NO_x – larger quantities the higher the temperature of combustion [4-11].

We can see here the contradiction in the engine concept: the higher the combustion temperature – the higher the efficiency of the engine and its performance, but greater toxicity of exhaust gases.

It is necessary to reconcile efforts of minimizing production and direct maintenance costs of the engine, and ecological requirements.

Regardless of acquiring information about the amount of undesirable exhaust components produced by the engine during flight, it cannot be forgotten that the quantitatively largest air pollution is in the airport area where huge amounts of carbon dioxide are emitted and at the same time oxygen is absorbed.

As an example, let us consider B767 aircraft taking off and landing at the Frederic Chopin Airport in Warsaw (the airport can be regarded as medium-sized in terms of daily and annual number of operations).

Knowing the characteristics of the engine and current fuel consumption, tedious calculation of the amount of produced carbon dioxide in the four phases of aircraft movement was conducted: take-off, climb to 3000 ft., approach, and taxiing before take-off and after landing. The accuracy of the calculations was verified by the current fuel consumption in this cycle. It was found that during take-off (lasting 45 seconds), climb (95 s),

descent (317 s) and taxiing (970 s) the two aircraft engines consumed a total 1340 kg of fuel emitting 4130 kg CO_2 into the atmosphere, UHC – 4 kg, CO – 16 kg and NO_x – 24 kg. At this time, 4165 kg of oxygen was consumed.

Based on similar calculations - on the North Atlantic route (approx. 9.5 hours), the amount of emitted CO_2 reached 155 170 kg (!) and 506 kg of nitrogen oxides (!).

4. Quantitative evaluation of the exhaust gas turbine aircraft engines content.

The intention of the authors is to draw attention of the aviation professionals to the fact that amount of exhaust from the turbine engine is so significant that may adversely change the ambient air near to the aircraft[1].

Table 1 summarizes the jet turbine engines basic data, while the Tab. 2, helicopters turbine engine, and turboprop used by the Polish Air Force.

[1] The fighter aircraft jet engine with afterburner emits as much carbon dioxide as column about 6000 cars at a speed of 90 km/h.

Tab. 1. Basic parameters of the turbine jet engines

No.	Aircraft	Engine	Thrust [kN]		SFC [kg/kN·h]		Σm_{pal} [kg/s]		m_{pow} [kg/s]
			max	with A/B	max	with A/B	max	with	
combat aicraft[2]									
1	MiG-17	1x WK-1F	26.5	33.2	111	204	0.82	1.88	48.2
2	MiG-21	1x R-11	38.3	56.4	96	235	1.02	3.68	64.5
3	Su-22	1x AŁ-21	76.0	110.0	88	190	1.86	5.81	104.0
4	MiG-29	2x RD-33	49.4	81.4	73	196	1.00	4.43	77.0
5	F-16	1x F100-PW-229	79.2	129.5	69	205	1.52	7.37	120.2
training aircraft									
6	TS-11	1x SO-3	9.8	-	108	-	0.29	-	18.2
7	I-22	2x K-15	14.7	-	102	-	0.42	-	23.0
commercial aircraft									
8	B-767	2x CF6-80C2	276.0	-	33.5		2.60	-	159[3)]
9	B-777	2x GE90	388.8	-	30.0		3.24	-	161[3)]
10	A-320	2x CFM56-5	138.8	-	58.0		2.23	-	71[3)]

Tab. 2. Basic parameters of the turbine engines operated in the Polish Air Force

No.	Aircraft / Helicopter	Engine	Power [kW]	SFC [kg/kW·h]	Σm_{pal} [kg/s]	m_{pow} [kg/s]
helicopters						
1	Mi-2	2x GTD-350	294	0.475	0.04	2.20
2	Mi-8, Mi-14	2x TW2-117	1100	0.394	0.12	8.10
4	W-3	2x PZL-10W	660	0.408	0.07	4.50
4	SW-4	1x RR 250	340	0.370	0.03	1.73
turboprop aircraft						
8	An-12	4x AI-20	2909	0.360	0.29	20.70
6	An-28	2x TWD-10B	700	0.387	0.08	4.60
7	C-130	4x T56	3425	0.329	0.31	14.51
8	CASA 295	2x PW127	2180	0.273	0.17	8.49

On the basis of this data, emission of CO_2, H_2O steam and nitrogen N_2 as well as remains of O_2 in the exhaust gas were calculated. Important is the fact that the fuel consumption (in seconds) while the afterburner is working is about 3 – 4 times higher than during maximum thrust range without afterburner.

Figure 5 in the form of pie charts illustrates the quantitative changes in the gas composition flowing through the engine duct. The size of the areas of the diagrams were chosen (equally in all cases) in proportion to the gas mass flow for each type of the engine. The length of the arcs on the diagrams circuit shows the mass percentage of H_2O, N_2, O_2 and CO_2 in the inlet air and exhaust.

[2] The airflow, only through the inner duct of the engine (core airflow).

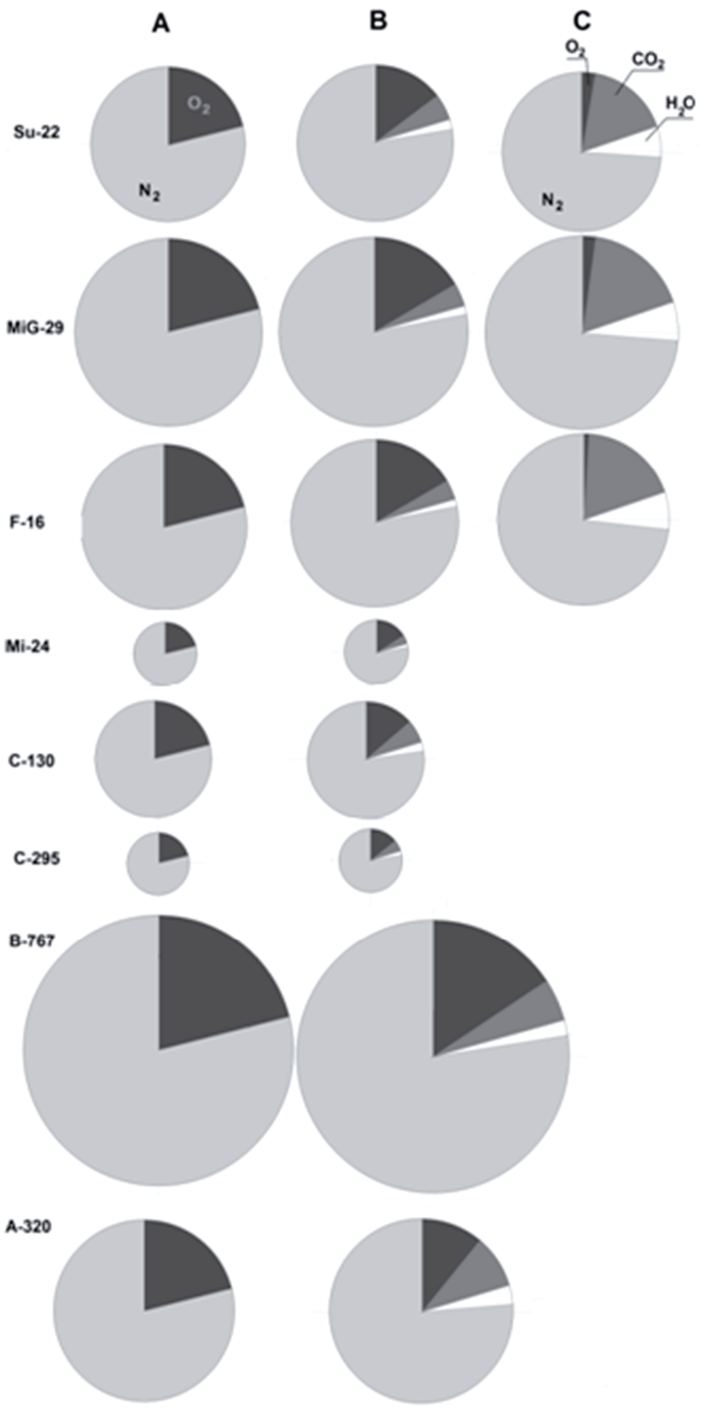

Fig. 5. Diagrams of the aircraft engines quantitative proportions (in kg s): A – engine inlet air with nitrogen (N_2) and oxygen (O_2) content, B – the exhaust gas (containing N_2, O_2, CO_2) at max. power, C – with afterburner

Quantitative comparison of the intensity of the airflow through the turbine engines is shown on diagrams (drawn on the same scale) for a few selected types of the aircraft and helicopters used in the Polish Air Force and three commercial aircraft. It is noteworthy that demand for air is many times smaller for the turboprop and turbo shaft engines compared to turbine engines operating at maximum power and thrust ranges (without afterburner). Afterburner eliminates the oxygen in the exhaust gas. This has an impact on the amount of carbon dioxide emission[3].

[3] In Aviation, limits for CO_2 emission has not been established yet, despite the fact that one aircraft engine "produces" it's much more than piston car engine.

5. Diffusion of aircraft engine exhaust in the airport area

The hot exhaust gases of gas turbine engines are a mixture of the inlet air remains (N_2 and O_2) and the combustion products (primarily CO_2 and H_2O) which include pollutants. The low density of the exhaust gases cause their upward movement in the surrounding cool air (compared with the exhaust gas temperature up to several hundred Celsius degrees). Exhaust gas stream is gradually mixing with ambient air and creates several layers in the atmosphere according to the current density changes depending on the ambient temperature.

Figure 6 shows the projected image of aircraft exhaust during take-off phase. The figure also shows the probable distribution of the CO_2 depending on height above the ground.

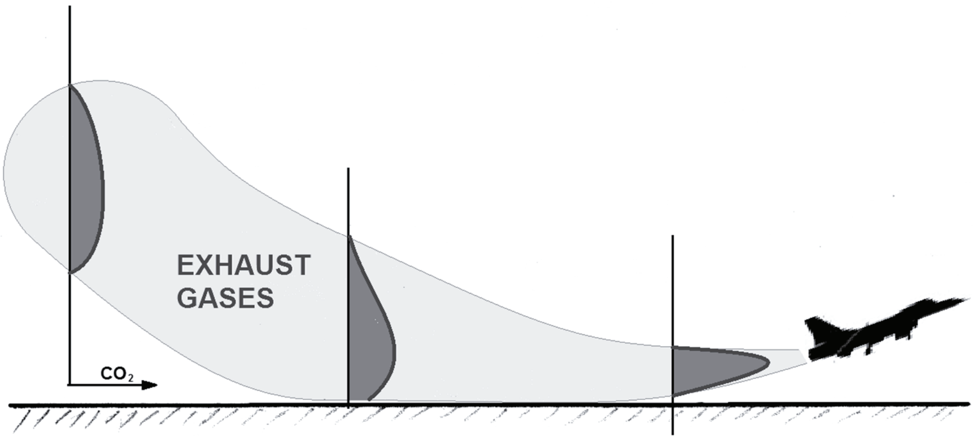

Fig. 6. Zone of the carbon dioxide concentration during aircraft take-off

Carbon dioxide CO_2 falls and lingers long on the ground. Fig. 7 shows distribution of CO_2 quantity after aircraft take off with an indication of its mass, „spilling” over the ground as time goes. This is because that (under the same conditions of pressure and temperature) the density of carbon dioxide is 1.5 times higher than the density of an air. Long-term stagnation of CO_2 at the ground is due to lack of wind and grassy cover.

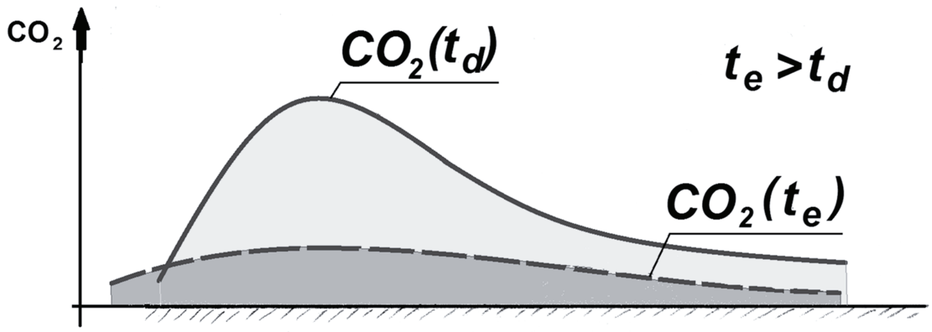

Fig. 7. Area of CO_2 after aircraft take off: $CO_{2(td)}$ - an area with a high content of CO_2 after time t_d from take-off, $CO_{2(te)}$ – an area with a high content of CO_2 after a longer time from take-off

Calculated on the engine characteristics basis the mass flow rate of exhaust gases and knowledge of the aircraft take-off duration allow to estimate the amount of CO_2 „left” at the surface of the runway and oxygen deficiency in the surrounding atmosphere.

The corresponding numbers are listed in Tab. 3 also in the conditions without and with afterburner for three types of combat aircraft.

Summation

Analysis of the data presented in the article allows drawing a number of conclusions about environmental threats level during aircraft take-off in different weather conditions. Definitely more favourable situation is during the windy weather compared to windless conditions. Similarly in the summer, because off the warm air combustion gases are rising higher, while in the winter exhaust gases are cooled quickly and lying at the ground due to the low temperature and higher air density. These considerations lead to the conclusion that the smallest ecological threats to the technical staff are during take-offs from aircraft carriers, which flows into the wind at a speed of several tens of knots leaving exhaust astern.

In addition, much better mixing effect of the exhaust with ambient air has turbofan engines, compared to those with low bypass ratios.

The final answer to questions about threats to the technical staff can be obtained after a detailed study of the carbon dioxide concentration distribution zones and oxygen minimum zones (a task for us - engineers) and determine the safe limits of these gases for human (a task for medical services).

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