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ANALYSIS OF THE WIND DEPENDENT DURATION OF THE CRUISE PHASE ON JET ENGINE EXHAUST EMISSIONS

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Abstract

Nowadays more and more attention is paid to minimizing the costs of air operations. The largest share in the cost of the flight is the cost of consumed fuel. Taking into account the external conditions, having impact on the aircraft, such as wind direction and magnitude when planning the aircraft trajectory it is possible to reduce flight time and thus reduce fuel consumption. An additional advantage is the simultaneous reduction of pollutants in the jet engines exhausts. In the times of pro-ecological trends and concepts (e.g. Clean Sky, Single European Sky, CORSIA) this aspect is of crucial importance. The emission of selected pollutants in the jet engine exhausts (NOx, CO and HC) emitted during the flight of a business jet on the route whose cruise phase was assumed 1000 km long was determined in the article. The aircraft used in the research was Gulfstream GIV, powered by two Rolls Royce TAY 611-C engines, for which a cruising altitude of 10 km and a flight speed of 0.8 Ma were assumed. The thrust necessary for the flight at these cruise parameters was set, and then the engine thrust appropriate for the flight and the corresponding specific fuel consumption were determined. On this basis, based on the available ICAO data, the emission of selected pollutants in tis engines exhausts was determined for windless conditions. Next, the analysis of the impact of wind - its magnitude and direction – on the emission of these pollutants was made. The results of the conducted analyses are presented in diagrams and discussed in the conclusions.

Keywords: *air transport, jet engines, air pollution, emission, exhausts, wind impact*

1. Introduction

Wind plays an important role in planning of a safe aircraft journey, especially its start and end, that is, take-off and landing operations. It is known that the headwind is preferred at the start of the aircraft, because it increases the lift and the aircraft requires a shorter run to airborne. During landing, the lead headwind wind is also preferred because the aircraft requires less runway at touchdown. In turn, during the flight, especially during the cruise phase, which constitutes its longest part, winds affect the plane's speed. Therefore, it is important to take winds magnitude and direction into consideration if the aircraft wants to stay on schedule. For instance, tailwinds make travel faster and save fuel, while headwinds have the opposite effect. In other words, in the presence of tailwinds, the speed of the aircraft relative to the ground (termed 'ground speed' or 'velocity over ground') increases by the magnitude of wind, although the flight speed relative to the air remains constant. In case of headwinds, the opposite effect occurs.

To illustrate how important it is to plan a flight trajectory in terms of the flight time and fuel savings, Air India airline example can be taken. In October 2016 this airline lengthened the flight trajectory from Delhi to San Francisco by 1,400 kilometres, but due to favourable winds on this route the flight time of the journey shortened by 2 hours (from 16.5 to 14.5 hours, or by 12%).

During natural air movements, it therefore is possible to shorten the flight time and, consequently, reduce fuel consumption, which obviously brings measurable (financial) benefits. This positive effect of headwind is also correlated with lower emissions of pollutants in jet engine exhausts, which is another advantage of careful planning of the aircraft mission. In addition, this last aspect is to be discussed in this article, the aim of which is to show the relationship between the changes in the direction of the wind on the amount of pollutants emitted in the exhaust of its engines.

2. Analysis of the impact of wind on emissions of pollutants in the jet engine exhausts

The business jet Gulfstream IV aircraft equipped with two Rolls Royce TAY611C engines was used in the research. It was assumed that the distance to be covered in the cruise phase is 1000 km long and that the plane overcomes this distance at the speed of 0.8 Ma at a height of 10000 m. On this basis, a reference flight time can be determined, i.e. in reference windless conditions:

$$V_{flight} = \mathrm{Ma} \cdot \sqrt{k \cdot R \cdot T}\ , \tag{1}$$

where:

Ma – Mach speed of the aircraft,
k – exponent of adiabatic for air equal to 1.4,
R – individual gas constant for air,
T – ambient temperature (in the analysed case at 10 km),

$$t_{flight} = \frac{L}{V_{OG}}\ , \tag{2}$$

where:

t_{flight} – flight time of the aircraft in the cruise phase,
L – distance covered by a plane in the cruise phase,
V_{OG} – flight speed of the aircraft relative to the ground.

It should be noted that the flight time of the aircraft is directly dependent on the flight speed. In case of windless conditions, the flight speed of the aircraft measured in relation to the air is equal to the ground speed. In case of the impact of wind, the velocity relative to the air does not change, while the ground speed changes, and, consequently, the flight time changes. More precisely, in case of favourable winds (tailwinds), the ground speed increases and, consequently, the flight time decreases, whereas in case of headwinds, the situation is opposite.

The idea of wind distribution on the example of tailwind is shown in Fig. 1. The wind affects the plane at a certain angle relative to its central axis, therefore the analysis takes into account the wind component parallel to the central axis, in the drawing described as V_x.

Table 1 shows different lengths of the flight time, resulting from the wind direction and magnitude (headwind, tailwind or windless conditions).

Knowing the flight time, the emission of pollutants in the jet engines exhausts can be computed with the use of the formula [5]:

$$E_z = EI_z \cdot 10^{-3} \cdot K \cdot SFC \cdot t \cdot l\ , \tag{3}$$

where:

E_z – emission of a particular pollutant z in exhausts [kg],
EI_z – emission factor for a particular pollutant z, depended on the type of engine and the range of its run [g/kg],
K – engine thrust [N],
SFC – specific fuel consumption [kg/(N·h)],
t – engine run time at a given thrust [h],
l – number of engines.

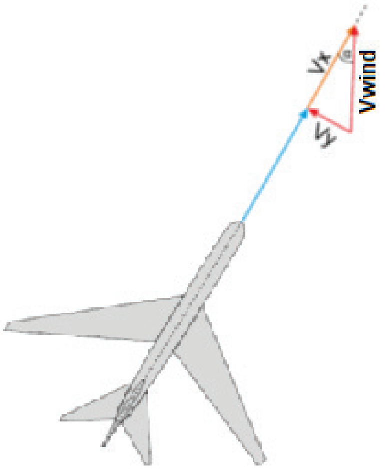

Fig. 1. Distribution of wind vector V_{wind} on V_x and V_y components

Tab. 1. Change in flight time resulting from the change in the wind magnitude and direction

	Headwind		No wind	Tailwind	
V_x [km/h]	-86	-43	0	+43	+86
V_{OG} [km/h]	776	819	862	905	948
change in the flight time [%]	110%	105%	100%	95%	90%
t_{flight} [min]	77	73	69	66	63

Emission factors (EI) that were taken into account for the analysis come from the ICAO Databank [3]. These factors are given for a given range of operation of a given engine, but for LTO (Landing and Take-off Operations) conditions, i.e. up to the altitude of about one kilometre (3000 feet). To apply them to the cruise phase, they should be multiplied by the reduction coefficients depending on the environment parameters, i.e. total pressure and total temperature at a given altitude at a known flight speed.

As it results from the formula (3), the thrust and SFC are required to determine the emission. Such values can be read from the speed-altitude characteristics of the jet engine showing the relationship between the engine performance and the conditions of its operation (cruising altitude and cruising speed). To select properly the range of the engine's operation to the airframe performing a given phase of the flight, its thrust required for the flight must be determined [2].

$$P_n = \frac{N_n}{V}, \tag{4}$$

where:
P_n – thrust required for the flight
V – flight velocity
N_n – power required for the flight, determined from the formula [2]:

$$N_n = \frac{C_x}{C_z} \cdot m \cdot g \cdot V, \tag{5}$$

C_x – drag coefficient,
C_z – lift coefficient,
m – mass of the plane,
g – acceleration of gravity,
V – flight velocity.

Knowing the value of the thrust required for the flight, from the speed-altitude characteristics of a particular engine it is possible to select both a safe value of the thrust (which means such a value that guarantees performing the flight) and the corresponding SFC [1].

Figure 2 shows the diagram of the flight required for the flight for an exemplary business jet – Gulfstream IV at the altitude of 10 km and then it was compared to the performance of its two Rolls Royce TAY 611-C engines [1, 6] at this altitude.

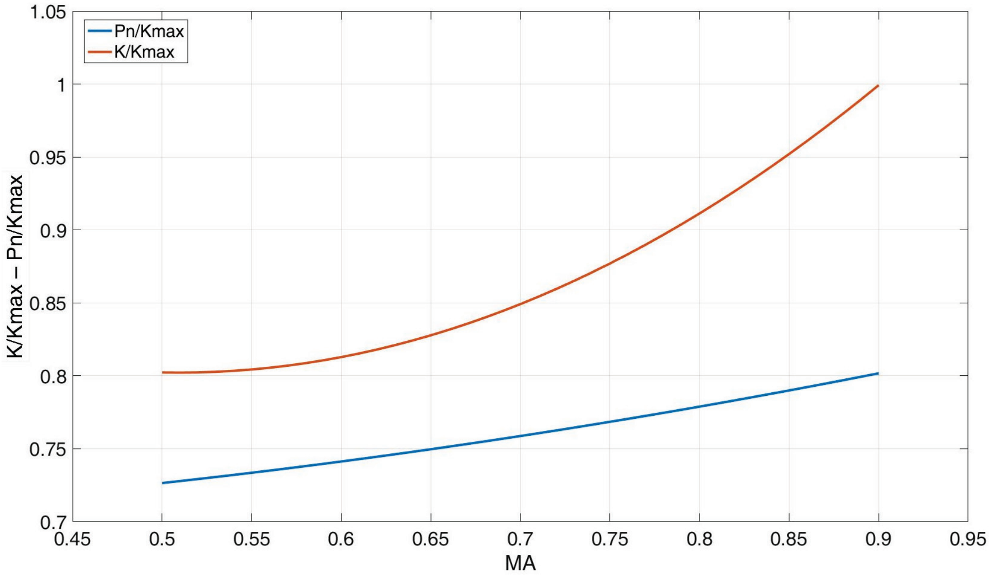

Fig. 2. The thrust required for the flight for the Gulfstream IV equipped with two TAY 611-C engines

3. Analysis of the obtained results

For such determined parameters of the engine performance, the emission of NOx, CO and HC was determined in cruise phase for the Gulfstream IV aircraft at the speed of 0.8 Ma and the altitude of 10000 m.

Tab. 2. Change in emission of NOx, CO and HC resulting from the change in the flight time

	Headwind		No wind	Tailwind	
change in the flight time [%]	110%	105%	100%	95%	90%
E_{NOx} [kg]	77.724293	73.633541	69.95186377	66.62082263	63.59260342
E_{CO} [kg]	5.2038601	4.9299728	4.683474116	4.460451539	4.257703742
E_{HC} [kg]	0.6690217	0.63381	0.60211954	0.573447181	0.5473814

The results presented in Fig. 3 show the change in emissions of selected toxic compounds depending on the flight duration. Emission of NOx is the biggest, which results from a big value of the NOx emission factor (EI_{NOx}) [4]. This value depends on the high engine load, which leads to high temperature of exhaust gases. The higher the temperature of the exhaust gases, the higher the NOx emission and the lower the CO and HC emission, which results from the near-complete combustion. NOx emission increases with the increasing duration of the flight, and the difference between this emission for the shortest and longest flight time is 14 kg.

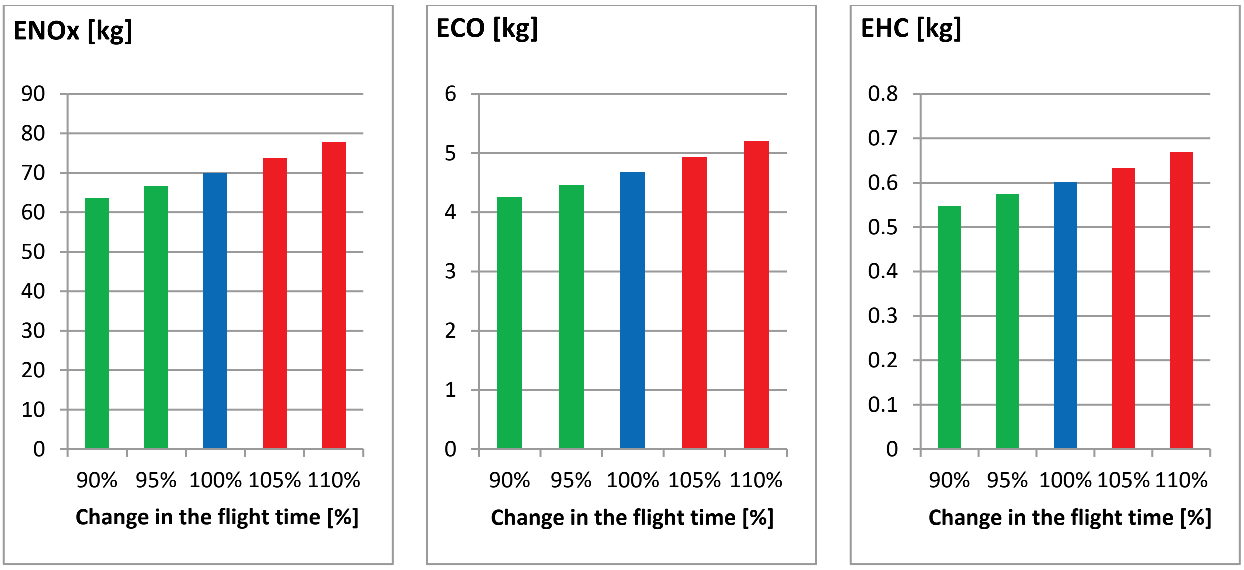

Fig. 3. The change in emission of NOx, CO and HC [kg] with the change of the flight time [%] (windless conditions = 100%)

It is noteworthy that there is no symmetry in the difference in emission of pollutants due to lengthening and shortening the flight time. In the case of NOx, the difference between the most preferred variant (tailwinds) and the windless variant with a flight time difference of 6 minutes is 6.5 kg (9.42%). On the other hand, when extending the flight time by 6 minutes (due to headwind), this difference is about 8 kg (11.6%) in comparison to the windless variant. Similar relationships can be observed for other pollutants (CO and HC). It should also be noted that in the case of CO and HC, differences in their emission expressed in kilograms are not significant, however, in percentage terms; they are at a similar level as NOx.

Based on the obtained results, it can be stated that taking into account the distribution of winds when planning the flight trajectory of the aircrafts, it is possible to reduce the emission of toxic compounds in the engines exhausts. In addition, this brings an additional advantage, which is the simultaneous reduction of the fuel consumption, which in addition to the environmental aspect is beneficial in economic terms.

4. Conclusion

This article shows how the wind can affect the duration of flight. Changing the flight time on an assumed flight path causes a change in the emission of toxic compounds in the jet engines exhausts. To minimize these emissions, as well as the fuel consumption, a flight trajectory should be planned for the most favourable external conditions. The changes in emissions during one journey seem to be low; however, in relation to global air traffic these differences will be significant and should be taken into account in the process of multi-criteria optimization of the flight trajectory.

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