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Performance and Emission of the Aircraft with Hybrid Propulsion During Take-Off Operation Cycle

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ABSTRACT

The paper presents the energy consumption and emissions of pollutants in the exhausts during the take-off operation mission of a Short Take-Off and Landing (STOL) aircraft equipped with a traditional and hybrid propulsion system. This research is part of the contemporary trend of research aimed at reducing the impact of aviation on the natural environment. The analyzed propulsion system consists of turbine engines and electric motors cooperating with them. In this work, on the basis of data from flight tests, the energy requirement for the aircraft to perform the intended mission was determined. On this basis, fuel consumption and the corresponding pollutant emissions were determined for an aircraft with a traditional power unit. For comparison, an aircraft with a hybrid propulsion system with the same mass as an aircraft with a traditional propulsion system was used. Then, energy consumption, fuel consumption and emission of CO_2, CO, NO_x, VOC, PM_{10} and $PM_{2.5}$ were obtained for both aircraft variants. The most important results of the conducted research include a reduction in CO_2 emissions by 23% and NO_x emissions by 46% in the case of the hybrid propulsion. This indicates potential benefits of using hybrid propulsion in aviation.

Keywords: hybrid propulsion, aircraft, energy consumption, pollutants emission, fuel consumption.

INTRODUCTION

The dynamic increase in the consumption of fossil fuels observed for decades has created the need for sustainable energy development. In addition, the pollutants present in the exhausts have a negative impact on the environment and climate. In the case of air transport, the main problem accompanying the development of air transport are the products of aviation fuel combustion - kerosene - emitted in the exhaust gases of aviation turbine engines. These are the following chemical compounds: nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon dioxide (CO_2), carbon monoxide (CO), unburnt hydrocarbons (HC) and particulate matter (PM) as by-products of combustion. Gases and particulates emitted by aircraft engines during the flight of aircraft accumulate in the atmosphere near the busiest air routes, mainly in northern latitudes. In addition, due to the nature of the aircraft's operation during take-off and airport-proximate operations, an increase in nuisance related to the emission of pollutants and noise occurs in the airport-proximate areas. These compounds, as a result of further photochemical reactions in the atmosphere, cause many adverse phenomena - acid rain, photochemical smog, increased tropospheric ozone concentration, greenhouse effect, etc. In addition, many studies show association between exposure to air pollution and the risk of diseases such as chronic and acute respiratory diseases, lung cancer, cardiovascular disease and premature deaths [1–6]. The problem of emissions is all the more important because in the last sixty years fuel consumption in aviation has increased so significantly that this market segment is now perceived as one of its main consumers.

Preserving natural resources and reducing the negative impact of air transport on the environment and climate is of paramount importance. Therefore, legislative solutions are introduced - e.g. CAEP (Committee on Aviation Environmental Protection) standards and the CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) program [7], which aim to reduce fuel consumption, reduce emissions and noise for subsonic passenger aircraft. The European Union has set a very ambitious target to significantly reduce the environmental impact of air transport - achieving a 75% reduction in carbon dioxide emissions, a 90% reduction in nitrogen oxide emissions and a 65% reduction in noise emissions by 2050, based on the technical level in 2000 [8]. It is therefore necessary to significantly reduce fuel consumption and/or apply alternative energy supply (electric energy, hydrogen, fuel cells, etc.) [1, 9].

The new aircraft propulsion systems under development should meet the restrictive standards and demand, and should be characterized by high efficiency, fuel efficiency, low fuel consumption and lower emissions of pollutants into the atmosphere. Research is being conducted on modifications to aircraft propulsion to improve its performance [10–12].

Reducing the emission of harmful and toxic compounds into the atmosphere is an issue of energy and engineering nature. Many research centers around the world conduct design and conceptual research on the application of various solutions. One of them is the use of sustainable alternative fuels (SAFs) [13–18]. The use of such fuels is aimed at reducing carbon footprint and CO_2 emissions into the atmosphere. However, there are problems with the technology of obtaining such fuels (CO_2 capture from the air) or logistic problems. In addition, the economic aspect of using such fuels is debatable [19]. Another solution is the application of an electric propulsion. The use of electric motors brings a number of advantages, such as [20]:

- low level of vibrations generated by the propulsion unit;
- high specific power (power to weight ratio of the electric motor);
- high value of torque available from low rotational speed of engine shaft, thanks to which the propeller can work with the engine with high efficiency.

The energy needed to power these motors can be obtained from batteries. This is the easiest way to configure such a propulsion unit. Unfortunately, the large mass of the batteries, their low energy density limits the payload taken on board the aircraft or limits the range of the aircraft [21-26].

To overcome this problem, a hybrid propulsion can be used - a propulsion in which an additional source of energy, most often internal combustion, will be on board the aircraft. The application where the electric motor driving the propeller draws energy from the battery bank and the generator driven by the internal combustion engine is called a series hybrid [23]. In the series hybrid configuration, the propeller is driven solely by the electric motor (Figure 1).

The architecture of the series propulsion makes it easy to use it in a distributed (multirotor) propulsion. This type of propulsion is interesting as a range extender system - increasing the flight's range. Unfortunately, due to the energy circulation on board the aircraft and its energy demand, such a system is useless for aircraft with a maximum take-off weight (MTOW) above 2 tons [27].

In the case of larger aircraft structures with a MTOW above 2 tons, where the demand for power required for flight is greater, it may be interesting to use the parallel hybrid system [20, 21, 23], shown in Figure 2.

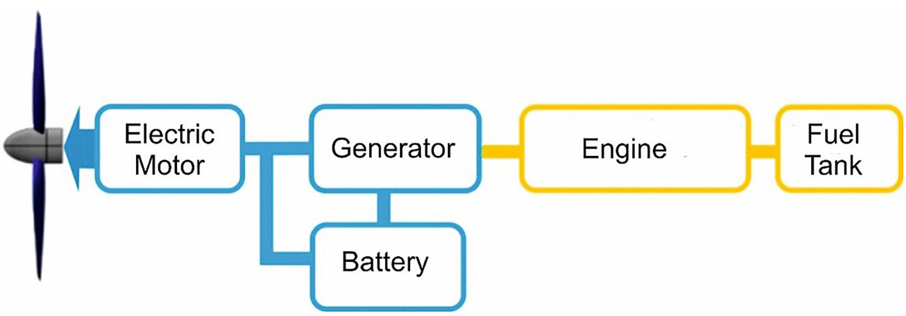

Fig. 1. Series hybrid configuration

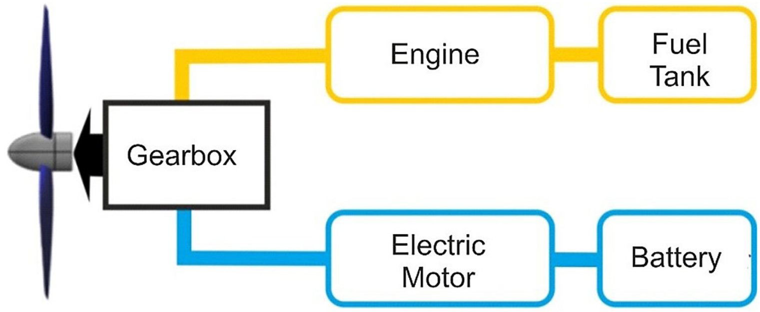

Fig. 2. Parallel hybrid system configuration

In a parallel hybrid propulsion system, the electric motor and internal combustion engine are mechanically connected to the drive shaft, often via a gearbox. The electric motor supports the internal combustion engine during take-off and climb to achieve the assumed flight parameters of the aircraft and the set operating parameters of the engine with the most favorable performance characteristics (ratio of developed power to fuel consumption). During horizontal (steady) flight, the electric motors can operate in generator mode, recovering some of the energy from the excess power of the internal combustion engine. The architecture of this propulsion system enables the development of various strategies for the consumption of energy accumulated on board the aircraft in the form of fuel and electricity in the batteries, the purpose of which is to optimize the propulsion operation in such a way as to reduce fuel consumption and thus the emission of pollutants into the atmosphere [27].

Currently, new developments for future aircraft are focused on electric and electric-hybrid aircraft, while the characteristics and especially the specific energy and thermal instability of the available battery technology cause serious problems [9]. To determine the strategy for the use of aircraft equipped with hybrid propulsion so as to use the maximum advantages of this propulsion, some research centers apply, for example, neural networks from the diesel-electric system or using a hydrogen cell [28-29]. Research is also being undertaken in scientific centers aimed at better management of energy accumulated on board the aircraft. For example, in [30] the authors overview the state of the art in architecture optimization and an energy management system for the aircraft power system. The basic design method for power system architecture optimization in aircraft is reviewed from the multi-energy form. The basic idea and research progress for the optimization, evaluation technology, and dynamic management control methods of the aircraft power system are analyzed and presented. In [31] the authors provide comprehensive insights into the recent progress in control system design and energy management aspects for electrical aircraft propulsion systems, together with a detailed analysis of the emerging challenges and technical barriers in this new and challenging research field.

RESEARCH PROBLEM

Based on the literature review, it can be stated that the issues of energy consumption, fuel and related pollutant emissions into the atmosphere are complex issues that require detailed research and analyses. It is worth noting that many studies focus on determining this impact in the area or vicinity of airports – during the Landing and Take-off (LTO) operation, where apart from emissions of harmful compounds in the exhausts, the problem of noise generation occurs. Due to the availability of data on HC, CO and NO_x emission indexes in the ICAO databases [32], it is possible to compute the emissions of these compounds for individual aircraft. Having data on air traffic at a given airport, it is also possible to determine the total emissions of particular compounds for a given airport in a given period of time, e.g. a year, e.g. [33]. It is also possible to make some analyses for only one selected LTO phase, e.g. climb, in order to determine the emission, e.g. [34].

The take-off flight stage consists of:

1) taxi-out – controlled movement of the aircraft on the apron, by means of its own propulsion, between the standstill point and the point from which the take-off will take place;
2) take-off – the phase of flight in which the aircraft moves from the take-off point on the runway and becomes airborne;

3) departure from the aerodrome and ascending – climb of the aircraft after take-off to the conventional moment when the aircraft reaches an altitude of 915 m (3000 ft).

This paper attempts to examine the impact of the use of hybrid propulsion on the emission and energy consumption only during the take-off and ascending, which are the most energy-intensive stages of the aircraft flight. In these stages the fuel consumption is also the biggest. Exhaust emission to the atmosphere is related to fuel consumption. For the exhaust components, such as CO, NO_x, VOC, HC, and PM, their emission indicators must be determined experimentally as they depend on the specific design of the engine concerned. To determine the emission values of these pollutants in an analytical way, the following relationships can be used [35]:

$$E_X = EI_X \cdot N \cdot SCF \cdot t \cdot l \tag{1}$$

where: E_X – emission of a particular pollutant [kg];
EI_X – Emission Indicator for a particulate pollutant [kg/kg fuel];
N – engine power [kW];
SCF – specific fuel consumption [kg/(kW·h)];
t – engine operation time at a given power value [h];
l – number of engines.

The formation of CO_2 as a result of fuel combustion by aircraft engines is directly proportional to the amount of fuel used, therefore modeling CO_2 emissions only requires knowledge of the fuel consumption values and the fuel-specific emission indicator. For jet fuel, this emission indicator for CO_2, EI_{CO2} = 3.155 kg/kg of fuel. Basic data on the emission of the exhaust gases at airports, as well as the methodology for determining emissions, are available in the literature [32], [35-37]. Using this data, it is possible to determine the emissions of pollutants present in aircraft engine exhausts.

DESCRIPTION OF THE RESEARCH OBJECT

The research object used to conduct the tests is the PZL M28 aircraft. It is a short take-off and landing (STOL) aircraft. As a result, it must be characterized by high available power (the difference between the power required for flight and the power of the propulsion system) in order to achieve a certain speed and flight altitude in a short time. This aircraft is a high-wing aircraft with a metal semi-monocoque structure. The wing is braced, the vertical tail is double. Depending on the version, it is equipped with two PZL-10S engines with a power of 690 kW each or two PW PT6A-65B engines with a power of 820 kW each. The paper will examine the variant equipped with PW PT6A-65B engines. Figure 3 shows the aircraft, and Table 1 presents its basic technical data.

In the analyzed case, the aircraft mission profile presented in Figure 4 was adopted.

The adopted mission profile is based on the M28 aircraft take-off procedure up to the altitude of 1 km, based on the actual procedure carried out for normal operating conditions. The aircraft trajectory adopted for testing comes from the standard procedure of the M28 aircraft carried out during normal take-off. This procedure is taken from

Fig. 3. M28 aircraft

Table 1. Basic technical data of PZL M28 (based on [38])

Parameter	Unit	Value
Wing area	S, m^2	39.72
Wing span	R, m	22.06
Maximum take-off mass	M_{max}, kg	7500
Overall Mass	M_{ov}, kg	4360
Maximum Speed	V_{max}, km/h	355
Cruise Speed	V_{CR}, km/h	290
Vertical Speed	W, m/s	11
Engine	-	PWC PT6A-65B
Propeller	-	Hartzell HC-B5MP
Take-off power	P, kW	2x820
Take-off Specific Fuel Consumption	SFC, g/kWh	326

Note: SCF [kg/(kW·h)] – specific fuel consumption.

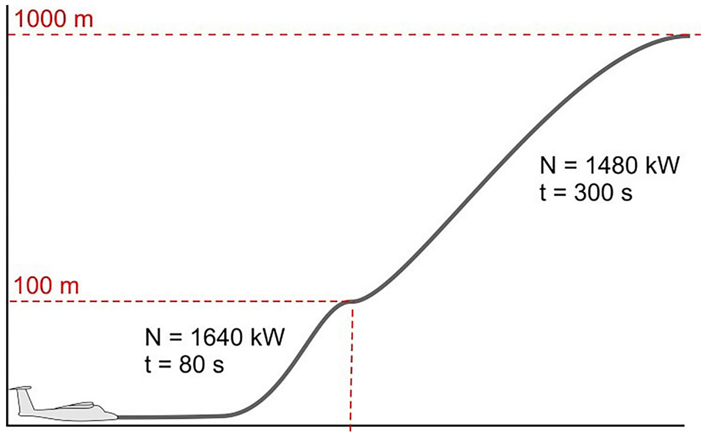

Fig. 4. Mission profile

the M28 flight manual [39]. Simplified data on the flight performance of this aircraft adopted by ICAO and general flight conditions are available at [40]. The adopted operating range includes the time needed to perform a given maneuver along with the corresponding engine operating range.

For each operating range, the fuel consumption of combustion engines was calculated. The obtained values were compared with the normative values given for the adopted aircraft mission trajectory, obtained from the M28 Aircraft Flight Manual [39]. The difference between the calculations and the results given in the manual is 1.1%, which can be considered as sufficient convergence of the results, validating the calculation scheme. Table 2 and 3 present the duration of individual maneuvers together with the corresponding operating range of the PT6A-65B engine [41].

These data made it possible to determine the aircraft's energy demand in a given stage of flight and fuel consumption during take-off and climb to the altitude of 1 km. The value of Emission Indexes adopted to determine the total emission for take-off depended on the fuel consumption and engine operating range (mainly operating temperature), depending on the propulsion variant used.

Table 2. Parameters of flight (for one engine) – take-off (based on [41])

Parameter	Unit	Value
Power T/O	N_{TO}, kW	820
Specific fuel consumption T/O	SFC_{TO}, kg/kWh	0.326
Time T/O	t_{TO}, s	80

Note: N [kW] – engine power; SCF [kg/(kW·h)] – specific fuel consumption; t [h] – engine operation time.

Table 3. Parameters of flight (for one engine) – climbing (based on [41])

Parameter	Unit	Value
Power CL	N_{CL}, kW	740
Specific fuel consumption CL	SFC_{CL}, kg/kWh	0.298
Time CL	t_{CL}, s	300

Note: N [kW] – engine power; SCF [kg/(kW·h)] – specific fuel consumption; t [h] – engine operation time.

PROPULSION CONFIGURATION

In the parallel hybrid system adopted for the analysis, the system should meet the following assumptions:
- high unit power,
- low level of vibrations generated by the propulsion unit,
- easy-to-use,
- high level of reliability,
- the total take-off weight of the aircraft is maintained at the same level as for the combustion variant.

In the proposed solution, a set of two EMRAX 268 electric motors connected in series is introduced between the engine and the propeller gearbox. These engines are designed to support the internal combustion engine during take-off. Such use of electric propulsion can reduce fuel consumption during the climb and increase flight safety. It will also extend the life of internal combustion engines, which will not have to operate in the range with the highest thermal loads (100% of nominal power). Figure 5 shows the diagram of the hybrid system analyzed.

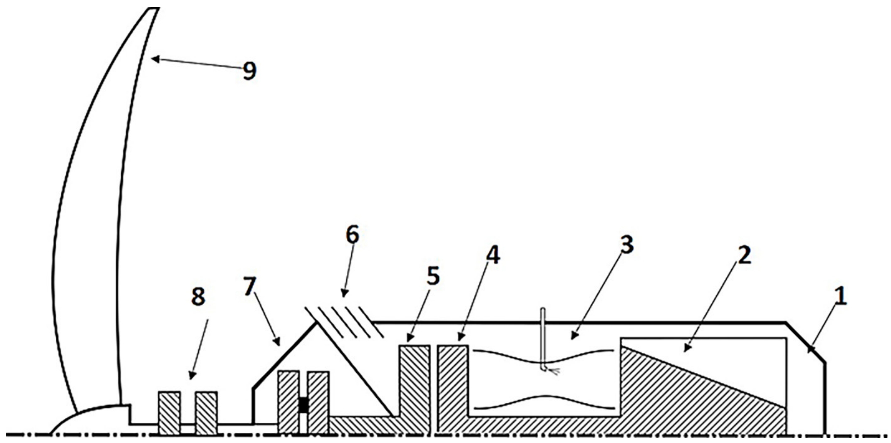

Fig. 5. Analyzed hybrid system: 1 – inlet; 2 – compressor; 3 – combustion chamber; 4 – high pressure compressor turbine; 5 – power turbine (free); 6 – outlet (exhaust); 7 – gearbox; 8 – electric motors stackup; 9 – propeller

Table 4. Technical data of hybrid propulsion system [43]

Parameter	Unit	Value
Engine Emrax 268		
Peak Power	N_{max}, kW	200
Continuous Power	N_{const}, kW	107
Engine mass	m_s, kg	20
Battery		
Battery mass	m_s, kg	120
Energy density	Q_e, Wh/h	450
Cumulated Energy	CE, MJ	194.4
Mass balance		
Overall engine mass	4 x m_s, kg	80
Battery mass	m_s, kg	120
Equipment	-, kg	100
Total mass	m_s, kg	300

Note: N [kW] – engine power.

During steady flight, the surplus power of the turbine engines can be directed to the battery bank through the generator operation of the electric motors. Then the system has the ability to store energy during flight.

As mentioned above, the source of energy to drive the EMRAX engines will be a set of batteries located in the fuselage of the aircraft. A set of batteries with a mass of 120 kg and an energy density of 450 Wh/kg was selected as the battery [42]. The proposed batteries are of the Li-Pol type and are developed for use in civil aviation. Table 4 shows the technical data of the additional components of the propulsion system along with their estimated weights. Cabling and elements necessary for the operation of the propulsion (regulators, energy converters) were adopted as the equipment.

SCOPE OF THE WORK

Based on the literature review and solutions regarding hybrid propulsion that may be used in aviation, a parallel hybrid propulsion system was adopted for the research object, which is the PZL M28 aircraft. In this system, it is assumed that two EMRAX electric motors support the operation of the combustion turbine engine during take-off and ascending, as indicated in Figure 4 and in Tables 2 and 3. On this basis, it is possible to determine the aircraft's fuel consumption and then calculate emissions of selected pollutants in the exhausts. To perform this analysis, Emission Indexes must be taken, which depend on the engine operating range. The analysis of determining fuel consumption and emissions will cover two variants - hybrid and combustion configurations, assuming the same take-off weight of the aircraft. This procedure is intended to demonstrate the expected benefits of using a hybrid propulsion.

DETERMINATION OF FUEL CONSUMPTION DURING TAKE-OFF OPERATION

On the basis of the collected data, it is possible to determine the energy consumption during the take-off operation by the aircraft for the assumed flight trajectory, as well as the fuel consumption for traditional and hybrid propulsion. The analysis assumes that the take-off weight of the aircraft is the same (7500 kg) for both cases. In the case of the hybrid propulsion, it was assumed that the aircraft takes off with fully charged batteries.

In the first stage of the flight - acceleration and detachment from the runway and ascent to an altitude of 100 m, the aircraft's power unit must work with the total power corresponding to the take-off power of the aircraft with a traditional power unit. However, aviation regulations specify that the internal combustion engine must be operated at a minimum of continuous power N_c during take-off. Therefore, in the case of a hybrid propulsion, the missing power will be compensated by the operation of the electric motors. For the second leg of the flight, the total power should correspond to the continuous power N_c for both internal combustion engines. In this range, the electric motors will work with all their available power, supplemented by internal combustion engines. The operating ranges of the propulsion unit are presented in Table 5.

On the basis of tables 1 and 5, it is possible to determine fuel consumption by internal combustion engines and battery energy consumption by electric motors. For internal combustion engines, the following formula was used to determine fuel consumption FC during take-off:

$$FC = N_S \cdot SFC \cdot t_S \cdot l \quad (2)$$

Table 5. Specification of the hybrid set

Parameter	Unit	Value
Take-off		
Total power	N, kW	820 × 2
Engine continuous power	N_c, kW	740 × 2
Motor power	N_e, kW	80 × 2
Climb		
Total power	N, kW	740 × 2
Engine continuous power	N_c, kW	540 × 2
Motor power	N_e, kW	210 × 2

where: N_S – engine power during operation mode;
SFC – specific fuel consumption;
t_S –maneuvering time;
l – number of engines.

The energy consumed by electric motors E_S can be determined according to the formula:

$$E_S = l \cdot N_E \cdot t_S \cdot \eta_S{}^{-1} \cdot \eta_p{}^{-1} \tag{3}$$

where: t_S – maneuvering time;
η_S – efficiency of the electric motor of 98%;
η_p – battery discharge efficiency for this type of construction of 90% (assumption based on test studies).

As mentioned above, the total emission is the product of the total fuel consumption and the EI corresponding to the given operating range for the given chemical substance X:

$$E_X = FC \cdot EI_X \tag{4}$$

Determination of emissions using the presented method is based on an experimental method. As mentioned in Chapter 2, the EI_X adopted for testing, determining the emission indexes of the tested compounds present in exhaust gases for the LTO phase, were included in [32] and result from tests conducted by ICAO. Due to the high costs and complexity of conducting similar certification tests, at the stage of the preliminary design described in the article, such a methodology is sufficient and widely accepted. The EI_X of particular pollutant, depending on the assumed level of combustion engine operation, are presented in Table 6 [44].

RESULTS

Based on the presented data, calculations of fuel consumption and energy efficiency of the proposed propulsion system were made. Figure 6 shows the differences between the total fuel consumption during take-off and ascent to the altitude of 1 km for tow tested variants – combustion propulsion and hybrid propulsion.

As can be seen, the difference in total fuel consumption for the entire take-off operation to the altitude of 1 km lasting 380 s was 12.3 kg (25.35% of the difference in favor of the hybrid propulsion).

Out of the 194.5 MJ of energy stored in batteries, electric motors consumed 124.7 MJ, which is shown in Figure 7. Based on the results obtained, it can be concluded that when the take-off is finished, there is still 69.8 MJ of electricity left in the batteries, which, with the engines operating

Table 6. Emission Indexes of NO_x, CO, VOC, PM_{10} and $PM_{2.5}$

Power level [kW]	EI_{NOx}, kg/kg_{fuel}	EI_{CO}, kg/kg_{fuel}	EI_{VOC}, kg/kg_{fuel}	EI_{PM10}, kg/kg_{fuel}	$EI_{PM2.5}$, kg/kg_{fuel}
540	0.00564	0.01379	0.002015	0.000515	0.000465
740	0.00669	0.00672	0.00072	0.00029	0.00026
820	0.00708	0.00536	0.00053	0.00026	0.00023

Note: EI_{NOX} [kg/kgfuel] – emission index for NO_X; EI_{CO} [kg/kgfuel] – emission index for CO; EI_{VOC} [kg/kgfuel] – emission index for VOC; EI_{PM} [kg/kgfuel] – emission index for PM.

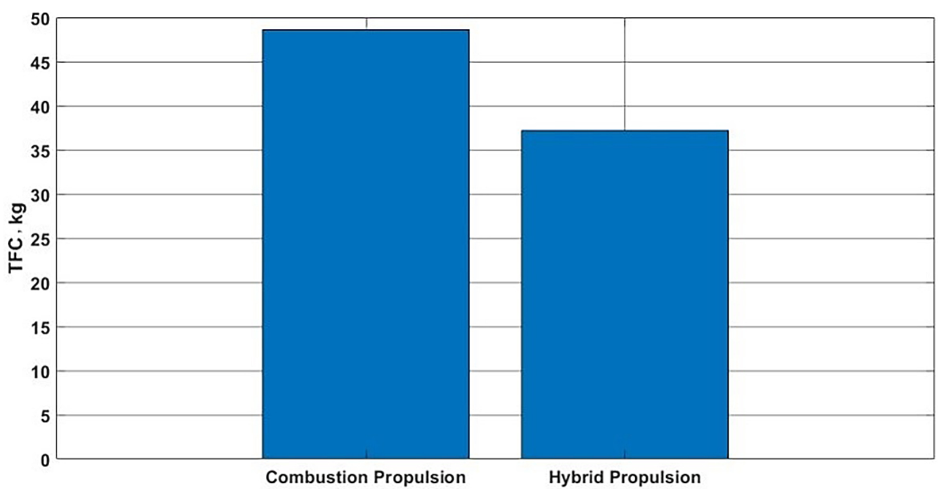

Fig. 6. Total fuel consumption for combustion and hybrid propulsion

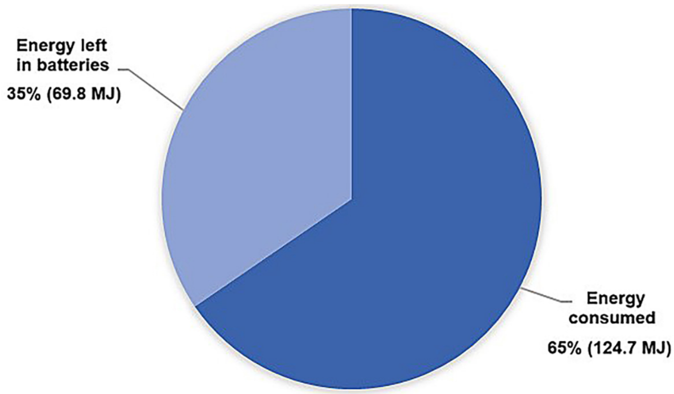

Fig. 7. The energy consumed from the batteries vs. the energy left in the batteries

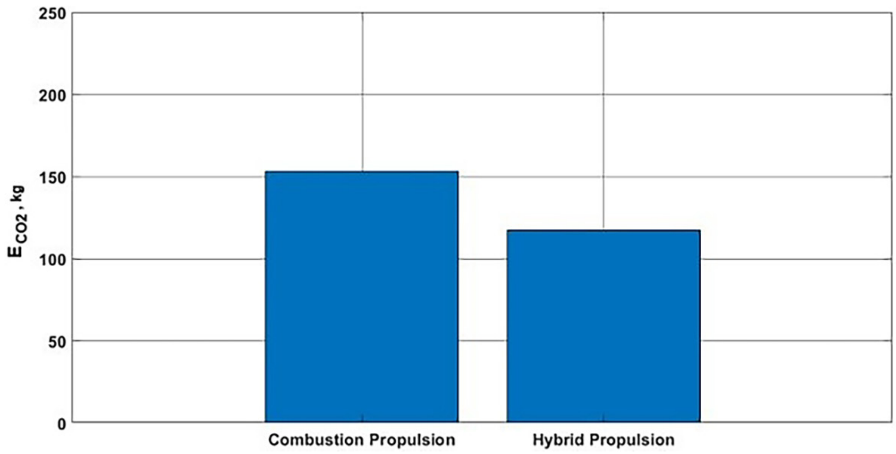

Fig. 8. Difference in CO_2 emission between combustion and hybrid propulsion

at full power, would be enough for about two and a half minutes (145 s).

The results relating to the total emission related to the analyzed flight trajectory look interesting. Figure 8 shows the difference in CO_2 emissions when using combustion and hybrid propulsion.

With the use of the hybrid propulsion, CO_2 emissions have been reduced by 36 kg (reduction from 153.2 kg to 117.13 kg). The percentage difference is 23% in favor of the hybrid propulsion. Considering the relatively short operation time, i.e. 380 seconds (6 minutes and 20 seconds), this reduction is significant. Figure 9 shows the emissions of other compounds during the take-off operation.

After application of the hybrid propulsion, NO_x emissions fell by 150 g, which is a 46%

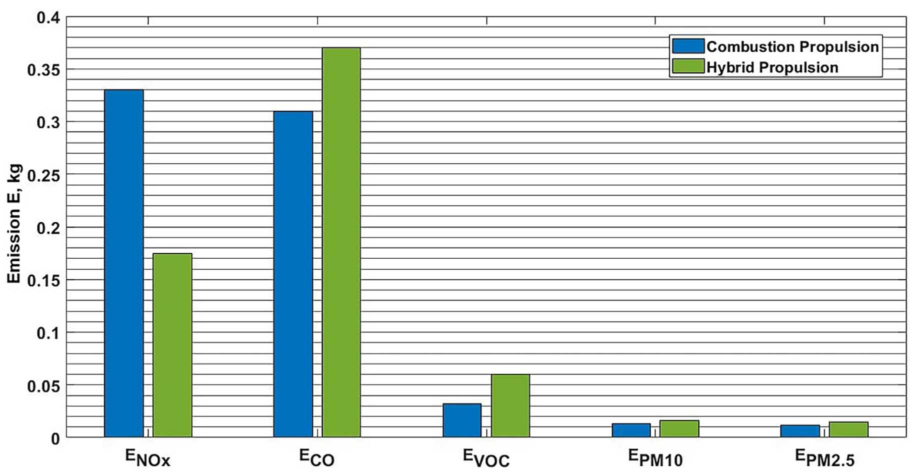

Fig. 9. Emissions of NO_x, CO, VOC, PM_{10} and $PM_{2.5}$ during the take-off operation

reduction in emissions. For other substances, the emission increased by 70 g (8%) for CO, 30 g (50%) for VOC and 3 g for PM. This is related to the operating range of the internal combustion engine - the engine operating outside the starting range operates at a lower temperature in the combustion chamber. This situation is conducive to limiting the formation of NO_x (which is formed at high temperatures as for the full power range). With regard to the remaining substances, their increase is caused by incomplete combustion at a lower temperature. However, the obtained differences are a few grams only and in global terms can be neglected.

CONCLUSIONS

Based on the literature review and analysis of the cited studies on parallel type hybrid propulsion, it can be concluded that these are mainly systems with a high degree of hybridization. In this case, the electric motors run throughout the flight. For this reason, they need a large number of batteries stored on board the aircraft, which worsens its operational performance – reducing the weight intended for luggage and passengers.

An innovation in the research presented by the authors is the use of a system with a low degree of hybridization. In this case, the electric motor only serves an auxiliary function during take-off or acceleration of the aircraft. Due to short-term operation, it does not require a large number of batteries, which impairs the aircraft's payload. Additionally, in the presented solution, during a steady flight, it is possible to use the electric engine as a generator to recharge the batteries. Thanks to this, the excess power of the combustion engine is used during steady-state flight. Even though the electric motor only works during take-off or acceleration of the aircraft, it reduces fuel consumption throughout the entire flight range of the aircraft, as take-off operations are the most energy-intensive. Moreover, the presented solution can be easily adapted to an existing aircraft without the need to introduce major structural changes to the airframe. Another innovation is the possibility of replacing the traditional power unit with a hybrid unit in an aircraft already in use, which is an advantage over conceptually developed hybrid propulsion.

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