Article citation info:
ORKISZ, M., KUŹNIAR, M. 3E – A new paradigm for the development of civil aviation. *Combustion Engines*. 2020, **181**(2), 3-10. https://doi.org/10.19206/CE-2020-201

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CE-2020-201

3E – A new paradigm for the development of civil aviation

Nowadays, in civil aviation, issues related to improving efficiency, reducing the costs of air operations as well as the negative impact of air transport on the environment are of increasing importance. These ideas allow the formulation of the paradigm relating to the development of air transport – 'more Efficiently, more Economically, more Eco-friendly – 3E'. The article presents in a cross-sectional and synthetic way research conducted by leading scientific centres around the world as well as prototype aviation constructions designed by companies from the aviation industry. Benefits and disadvantages of future propulsions, such as purely electric, hybrid and distributed propulsions, were presented. Conclusions were formulated regarding further possible directions of civil aviation development, taking into account the improvement of its efficiency as well as economic and ecological indicators.

Key words: *airplane, electric propulsion, hybrid propulsion, distributed propulsion, reduction of emission exhaust, reduction of noise, decrease of fuel consumption*

1. Introduction

Aviation is the branch of transport that has significantly contributed to globalization of the world. Accompanying the development of aviation, until recently, the 'Higher, Faster, Farther' paradigm lost its significance in the last years. The currently noticeable trend of aviation development leads to the fulfilment of criteria more favourable to the protection of man and his ecosystem. Permanently emerging cognitive and utilitarian research programs try to redefine the existing solutions for the needs of the new paradigm. Among the examples of these activities there are studies on improving the airspace capacity and more efficient airspace management, as well as the works on improving and optimizing the operation parameters of internal combustion engines as well as programs aimed at determining the design assumptions for propulsions based on hybrid, combined or all-electric systems. The effect of such solutions is the possibility to reduce journey costs by reducing fuel consumption, as well as noise and toxic emissions to the atmosphere.

Due to the above, the authors propose to replace the paradigm mentioned above with a new, more timely one, taking into account current trends – the 3**E**' paradigm – 'more **E**fficiently, more **E**conomically, more pro-**E**nvironment'.

The pro-environmental trend is reflected in the regulations developed and constantly improved in the scope of reducing the negative impact of air transport on the natural environment. The first international regulations regarding the reduction of fuel consumption, pollutants and noise emissions entered into force in 1972 (Annex 16 to the ICAO Convention) [29], and in March 2018 the new wording of Annex 16 entered into force. It regulates emission of pollutants and noise limits for newly designed aircraft structures in accordance with the recommendations of CAEP (ICAO Technical Committee for Environmental Protection).

At the same time, there emerge declarations, international research programs and initiatives of international, governmental and non-governmental organizations, as well as aviation companies who aim at the sustainable and responsible development of aviation. Such a development is possible to achieve through the following tasks [29]:

- stabilizing CO_2 emissions in the aviation sector at the level of 2020 (through so-called carbon-neutral growth),
- reducing CO_2 emissions in aviation by 2050 by 50% (compared to 2005),
- reducing the carbon footprint in air freight,
- fleet rejuvenation and modernization,
- investing in bio jet fuels (biofuels for aircraft turbine engines),
- reducing mass of aircraft,
- developing e-freight (called paperless cargo),
- developing lightweight ULDs.

Many research works are being currently carried out in line with the above-mentioned tasks, such as works related to increasing the efficiency of air traffic, e.g. the SESAR program. Within its framework, attempts are being made to develop a new approach to flight planning and to make more efficient use of cargo and passenger spaces in aircraft. In addition, research related to the optimization of flight trajectory in terms of minimizing flight time or fuel consumption indicate that it is possible to achieve a decrease in pollutants emissions and fuel consumption on a given route [24-29].

However, the goals assumed in the longer term (for the year 2050) require developing new technical solutions. Composite materials have a growing share in newly emerging aviation constructions, which clearly affect the decrease in flying vehicles mass. Propulsion efficiency has been increased by developing new propeller aerodynamic systems [31], as well as by increasing the exhaust gas temperature before the high pressure turbine in the case of turbine engines [5].

In order to increase further the efficiency of aircraft constructions, new aerodynamic solutions (e.g. the flying wing shown in Fig. 1) are being sought [21], as well as propulsion systems envisaged in future aircraft, such as distributed propulsion [4].

Received 25 January 2020; Received in revised form 6 April 2020; Accepted 10 April 2020
Available online 30 June 2020

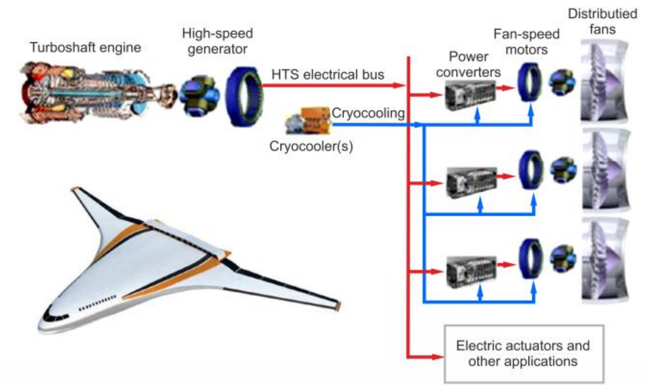

Fig. 1. Airplane in a flying wing configuration with a hybrid, distributed propulsion [21]

The distributed propulsion is characterized by the use of a number of electric motors (EM) together with propellers of a small diameter [31] or flow engines of the low trust class [4]. They are usually placed on the wing leading edge or at the fuselage. This division and location of the propulsion is aimed at improving the propulsion efficiency, improving the aerodynamic parameters of the aircraft and a better balance of energy consumption during the flight [7, 11, 20].

In the presented publication, the authors focused on the analysis and synthesis of the last of the above-mentioned research problems – the possibility of using propulsion systems in aviation based on hybrid, combined or all-electric drive.

2. Research problem

The current trend combining activities increasing the efficiency and effectiveness as well as the environmental performance (3E) of aircraft propulsions forces the development of new technical solutions or improvement of current ones.

One concept is to use an electric propulsion to propel aircraft. Electric motors are characterized by high efficiency, reaching up to 95% [10, 15, 34], and in relation to piston engines of the same power they show a better power-to-weight ratio. For comparison, the Emrax 268 engine, which weighs 11 kg, generates 110 kW of peak power and 500 Nm of peak torque [34]. In contrast, the Wankel AG 807 tgi piston rotary engine, which weighs 35 kg, for 75 kW of power, generates 80 Nm of torque [37]. In the case of an electric motor, attention should also be paid to [2, 3, 18]:

- lack of complicated equipment, nor heavy cooling and oil system,
- lower vibrations generated by the propulsion system, which, combined with the lower mass of the engine, allows building simpler and lighter systems integrating the propulsion with the plane,
- high reliability,
- simple operation.

Among other things, these properties have caused the popularity of the use of electric propulsion in both amateur modelling aircraft and unmanned aerial vehicles (UAVs). Initial selection of the engine for driving an unmanned vehicle requires first of all determining the take-off mass of the vehicle [1]. Based on this information and aerodynamic data, based on the known power method [6], the value of the power required for the aircraft flight is determined. The power of the propulsion system depends on the propeller efficiency for a given flight speed and the power received by the propeller.

It seems interesting to compare the performance of unmanned vehicles of short or vertical take-off (VTOL) presented, e.g. in [11], where the performance of combustion and electric vehicles with the same take-off mass is taken. It was shown that for the same take-off mass and same power generated at the start of the vehicle, the range of UAV equipped with electric propulsion is reduced threefold.

For short missions it is not necessary to construct complicated hybrid propulsion and purely electric propulsion is sufficient [14]. In addition, the authors show that all-electric propulsion systems are still too heavy, and the combustion-electric hybrid systems do not offer noticeable benefits over conventional configurations. However, they state that for a greater flight distance, hybrid technology constitutes a more advantageous propulsion system compared to a purely combustion system, even with the energy density for the battery of 500 Wh/kg. The authors also show that electric VTOL aircraft will not be able to cover a distance of 500 km, even with a minimum take-off mass. In addition, based on their computational research, the authors state that the use of distributed propulsion allows more efficient use of energy stored on board.

Among the studies on current trends in aviation technology, the use of electric and hybrid propulsions in small and passenger aviation is described, which was presented in the doctoral dissertation [23]. An interesting concept presented in the dissertation is the propulsion using ducted fans driven by electric motors. These fans generate up to 80% of the thrust necessary to flight. The electricity needed for the fans to operate and the missing value of thrust for the flight is generated by the turbine engine. This work also describes the concept of a by-pass turbine-electric engine. A traditional turbine engine would work in the internal channel of this engine and there would be no power turbine to drive the fan. Due to this arrangement, it would be possible to save fuel during the flight. The impact of this type of propulsion on reducing NO_x and CO_2 emissions during aircraft operation was also described.

Based on the cited research, it can be concluded that the main disadvantage of electric propulsion systems used in aircraft constructions is their high mass. The high mass of the batteries together with their relatively small capacity results in a low value of the energy density stored on board – compared to e.g. the energy density stored in the hydrocarbon fuel. These properties affect the limited range or duration of the flight, which are affected by increased requirement for power during manoeuvres, such as take-off or climb. Therefore, it seems interesting (until an energy source with sufficient energy density is developed) to develop a hybrid propulsion that would allow to increase the usable parameters of the aircraft.

A hybrid system is the one where the energy necessary for the flight of an aircraft comes from more than one source. The most common solutions are electric-combustion systems, where energy comes from both the combustion of hydrocarbon fuel and the energy accumulated in batteries. The system in which fuel cells are used to replace the combustion engine is also called hybrid. An important energy indicator determining the type and design of the propulsion system is so-called degree of hybridization [3, 10, 15, 16]. The degree of hybridization is the ratio of energy from the battery to the total energy accumulated on board the aircraft, and can be described by the formula (1):

$$\mathrm{H} = \frac{\mathrm{E_{Bat}}}{\mathrm{E_{Tot}}} \tag{1}$$

where: H – degree of hybridization, $\mathrm{E_{Bat}}$ – the amount of energy stored in batteries, $\mathrm{E_{Tot}}$ – total energy accumulated on board the aircraft.

At low values of the degree of hybridization, the amount of energy stored in the batteries is small compared to energy coming from an combustion engine or fuel cell. For high values of the degree of hybridization, it is the combustion engine or the fuel cell that takes over the role of an auxiliary energy source.

The hybrid propulsion can be constructed in series or in parallel and their schematic diagrams are presented in Fig. 2.

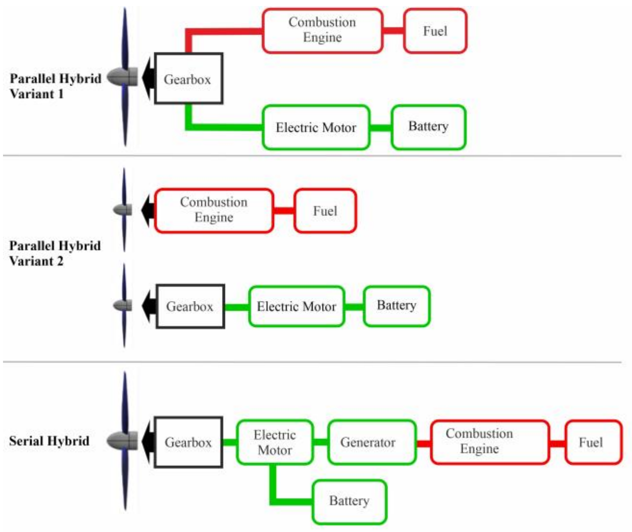

Fig. 2. Schematic diagrams of hybrid propulsion [8]

The serial propulsion is characterized by the fact that the propeller is driven exclusively by an electric motor [7-11]. The energy needed for flight in systems with a low degree of hybridization is generated by a piston or turbine combustion engine, e.g. APU engines or other solutions presented in [3, 28, 33].

The electrical system is complemented by the battery to provide energy when the combustion engine or fuel cell is not generating electricity. In systems with a high degree of hybridization, the combustion unit and electric generator are used to recharge the battery and maintain its capacity, thereby increasing the range and flight duration. The combustion engine-generator system is called a range extender. In this case, the role of the range extender can be taken over by a fuel cell, e.g. a hydrogen fuel cell, as in the AOS H2 motor glider [20].

In a hybrid serial propulsion system, the propeller is driven solely by an electric motor of dimensions adapted to the maximum energy requirements – energy consumption depends on the aerodynamic performance of the propeller and the requirements of the aircraft performing a given flight mission. A multi-propeller system, where each propeller is driven by its own electric motor, is also possible. Depending on the system layout and degree of hybridization, the combustion engine can work at a constant speed and constant level of developed power, which enables optimizing it for one specific design point, i.e. set the operating range of the internal combustion engine to work at its highest thermal efficiency. This will ensure the highest power obtained on the propeller shaft with the lowest specific fuel consumption of the engine. The engine drives a mechanically coupled generator that generates electricity, which is then fed into the energy management system. The power can be directed directly to the electric motor that drives the propeller or the power is divided between the battery (to charge it) and the motor driving the propeller. Such a system is safer due to the fact that the battery is a safety buffer in case of a failure of the charging system or running out of the fuel [10]. The energy management system also enables to supply additional energy from the battery to the aircraft's propulsion if the required power is higher than that which the charging system can provide. Thus, if the combustion generator or fuel cell possesses the parameters (obtained electric power) enabling efficient flight, the electric generator and battery can provide the excess power used for take-off and climb of the aircraft.

If the battery pack is properly selected for the airframe in terms of energy and mass, the aircraft with serial hybrid propulsion system can also operate in all-electric mode. This may be desirable from the point of view of noise and pollutants emissions reduction [29], especially during the take-off and initial climb phase [26, 27].

A parallel hybrid is a configuration in which the internal combustion engine and electric motor operate in mechanical coupling [11, 12]. In the case of a parallel hybrid propulsion system, the electric motor and the internal combustion engine are mechanically connected to the propeller shaft, often via a gearbox. For a system with a low degree of hybridization, an electric (of low power) motor will support the internal combustion engine during the take-off and climb to achieve the assumed rotational speed of the propeller and the steady engine parameters of the most favourable performance characteristics (the ratio of developed power to fuel consumption).

It should be noted that an implementation in which an electric motor drives one propeller and an internal combustion engine drives another propeller [11] is also considered a parallel hybrid. The total required power is divided between internal combustion engine and electric motor, which corresponds to the designated degree of hybridization of the structure. This enables to optimize the construction by applying a smaller internal combustion engine, as well as a properly selected electric motor. Compared to the serial configuration of the hybrid propulsion, the electric motor in the parallel hybrid propulsion system can be smaller and lighter because it provides only a certain amount of the total power and constitutes in this regard an auxiliary engine. Since the power obtained by the internal combustion engine is mechanically transferred to the propeller, there is no dedicated generator in such a system. This reduces the complexity and mass of the propulsion unit and positively affects its propulsion efficiency [31].

The application of this type of solutions in General Aviation (GA) aircraft was analysed in [9]. The authors point out that the use of traditional methods to determine aircraft geometry in the conceptual design phase is inadequate for hybrid or electric propelled aircraft. They propose to reduce the computed value of wing area obtained via computations using a traditional approach to design by increasing the power of the engine. The approach presented could be beneficial during the high-speed flight phase. When taking-off and flying at low speeds, the excess power needed may limit the overall range and duration of the flight. The authors rightly noticed that for the traditional configuration of the aircraft the most advantageous is the parallel system – an electric motor and internal combustion engine driving the propeller together. This is due to the characteristics of the combustion engine. The authors did not mention that the internal combustion engine achieves its greatest efficiency for the flight range, while in transient states it would be advisable to use an electric motor as a booster. This is because a serial propulsion or propulsion using range extender may be more advantageous when adopting propulsion using more than one propeller. The authors also state that hybrid and electric propulsion can be successfully used on light aircraft and GA.

Increasing efficiency (increasing range and reducing fuel consumption) and reducing environmental impact (reducing emissions) constitute the issue raised in [13]. The authors presented the possibilities of adopting aircraft structure optimization to reduce fuel consumption and increase the aircraft range. This issue is the foundation for multi-criteria optimization of the aircraft structure or flight parameters with the aim of improving the environmental and performance indicators of the aircraft. Optimization can relate to both the selection of aircraft flight trajectories and the reduction of aircraft mass. Properly designated flight path can significantly affect the performance of the aircraft and the propulsion system, such as fuel consumption or pollutants emission, as shown in [24-29]. On the other hand, the optimized mass of the aircraft significantly reduces fuel consumption, which is associated with lower power and thrust required for an aircraft's steady flight at a certain speed [20, 31]. Such an approach to aircraft design is inline with the '3E' paradigm.

The hybrid propulsion system combines the advantages of the systems based on hydrocarbon fuel and the systems powered by batteries [8]. It can contribute to more efficient operation of internal combustion engines assisted by an electric motor in transient states. In addition, hybrid designs offer greater flexibility for comprehensive aircraft design, such as distributed propulsion. This is possible because the power of an internal combustion engine can be transferred to light electric motors by means of wires instead of many heavy engines or drive shafts, as noted by the authors of [8]. The authors, after analysing various configurations of hybrid propulsion with different degrees of hybridization using a combustion generator, noticed the potential benefits of this type of assembly. They state that hybrid-electric and all-electric aircraft can revolutionize the propulsion and construction of the aircraft. However, to take full advantage of these concepts, new and innovative aircraft design methods need to be developed. Best performance is only achieved through a comprehensive approach in aircraft design. It is an approach where the airframe and propulsion system are designed simultaneously, and the design is optimized in terms of aerodynamics taking into account the interference between the airframe and rotors or propellers. This can ensure the efficient use of energy stored on board the aircraft in its various types.

The result of work on electric and hybrid propulsions are flying vehicles, both manned and unmanned, built in recent years.

Airbus has been developing the E_Fan aircraft concept since 2014. It is the vehicle with a wingspan of 9.5 m and an aircraft length of 6.67 m. The propulsion is responsible for two ducted fans with a thrust of 0.75 kN each, powered by 30 kW electric motors. The take-off mass of this aircraft is 550 kg, 170 kg of which is the lithium-polymer battery (li-pol). The E_Fan is a platform used for testing the concept of zero emission jet propulsion. An extension of this concept is the aircraft with so-called range extender – a combustion engine driving an electric generator, which is expected to be presented in 2020. A further development of this project is the concept of the E_Fan X passenger aircraft (presented in Fig. 3), where three traditional turbine jet engines are supported by the engine tested in the E_Fan aircraft. The electricity needed to drive it, is generated by combustion engines.

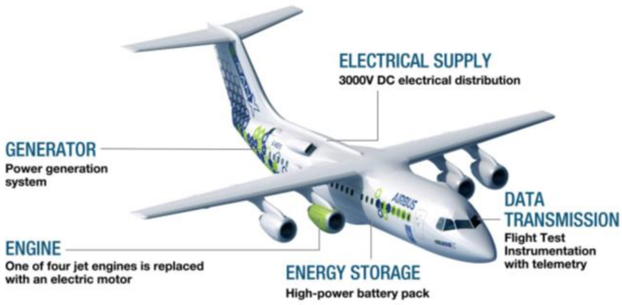

Fig. 3. The E_Fan X aircraft [31]

Pipistrel company has presented the Panthera aircraft [35] (cf. Fig. 5 – it is worth paying attention to the refined silhouette in terms of minimizing aerodynamic drag force), which is available in three variants: combustion, hybrid and all-electric. Each version is designed for different target groups of customers. The internal combustion engine is dedicated to people who need fast long-distance travelling, while the electrical system, which is the most environment-friendly solution, is mainly used for local communication. The hybrid system is a combination of these two concepts, however, the complexity of design and operation can increase operating costs.

Fig. 4. Pipistrel Panthera aircraft [35]

Constructions equipped with eco-friendly propulsions are also: the Boeing Phantom aircraft equipped with a fuel cell to drive avionics, the German Antares 18E motor glider – a high performance aerobatic vehicle equipped with a small electric motor providing the possibility of an independent take-off and a safer flight. A fuel cell version has also been developed.

The AOS 71[1] (Fig. 5) and AOS H2[2] motor gliders are noteworthy. They were developed by a consortium of Rzeszow University of Technology, Warsaw University of Technology, AGH University of Science and Technology and The Glider Factory 'Jeżów'–Henryk Mynarski. The first one is a purely electrical construction and the second one is a hybrid using a hydrogen fuel cell.

Fig. 5. The AOS 71 motor glider 71 [35]

Hybrid and electric propulsions have a significant disadvantage – it is the large mass of the propulsion system, which is particularly visible in the case of smaller aircraft. To increase aircraft propulsion performance, energy management on board an aircraft could be optimized [17].

Distributed propulsion constitutes an alternative to traditional propulsion systems. As previously mentioned, such a system is based on the use of many small electric motors or combustion engines. Low-thrust jet engines, fans or propellers driven by electric motors can be used. These can be all-electric as well as hybrid or combustion units. Propulsion elements can be placed along the leading edge of the wings [31], on the fuselage and even on the aircraft stabilizers. The purpose of the research on this system is to demonstrate that having the same power of a small engine assembly as the power of a traditional 'focused' power unit, it is possible to achieve more favourable performance characteristics, such as increasing thrust with lower fuel consumption and lower pollutants emissions into the atmosphere. Many scientific and research centres worldwide undertake work on these issues.

The company JOBY Aviation together with NASA runs the LEAPTech research program, which aims to build an electric aircraft using the amount of electricity available on board the aircraft more efficiently. Additional goals are to remove internal combustion propulsion and to reduce noise emission significantly. Therefore, the construction of an aircraft equipped with all-electric distributed propulsion was undertaken. The Cirrus SR22 aircraft served as a comparative base for research. The results of the research conducted were published, e.g. in [31]. To validate the design assumptions, the performance of the Cirrus 22 aircraft with a traditional propulsion system was compared with its LEAPtech development equipped with distributed propulsion of the same take-off power. The analysis was carried out with the CFD simulations and laboratory ground tests of wing flow by air flow generated by electric motor-propeller assemblies. Table 1 contains basic technical data for both aircraft, and Fig. 6 shows the LEAPtech aircraft.

Table 1. Comparison of technical data for Cirrus and LEAPtech aircraft [2]

	Cirrus SR22	LEAPTech
Take-off mass	1542 kg	1361 kg
Seats	4	4
Wing span	11.7 m	9.45
Aspect ratio	10.1	17.4
Wing area	13.5 m^2	5.1 m^2
Wing loading	114.2 kg/m^2	266.86 kg/m^2
Cruise speed	340 km/h	320 km/h
C_z for cruise speed	0.3	0.77

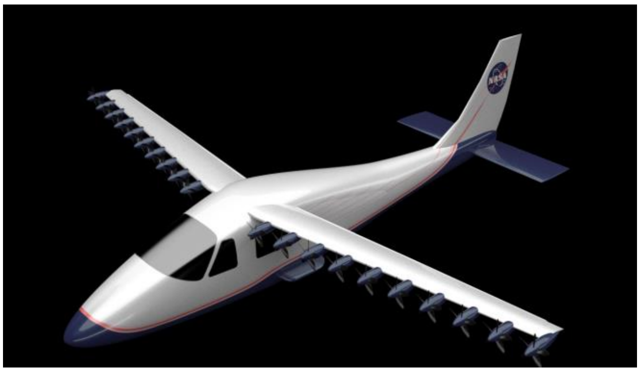

Fig. 6. LEAPTech concept aircraft [21]

As shown in Table 1, despite the reduction of the bearing surface by more than 2.5-fold, researchers estimate that the bearing force coefficient in the flight range will be more

[1] KBN/68/12823/IT1-B/U/08 pt. „New generation multifunctional two-seater motorglider".
[2] NCBR PBS3/A6/24/2015 pt. „Hybrid propulsion using fuel cells of light aircraft".

than twice as high. C_{zmax}, on the other hand, will be over 4 times higher due to the propellers placed on the wing leading edge. An accelerated airflow will flow around the upper surface of the airfoil much faster than in the case of a traditional aircraft design system, hence a significant increase in aerodynamic lift at the same value of energy put in the aircraft's propulsion.

The possibility of using distributed propulsion in the VTOL aircraft was described by the authors of [7]. They arranged the rotors in such a way that the vehicle could start vertically. Then, sequentially, the rotors together with the fixed wing would change the configuration for horizontal flight. Such a layout of the propulsion can bring measurable benefits in the form of more efficient energy distribution on board. An equally important element is the use of rotors to control the direction of flight of the aircraft, which reduce the number of complex elements of the aircraft control.

A number of studies, particularly represented by [21, 22], raised the idea ofdistributed propulsion for aircraft intended to replace traditional long-range passenger aircraft. There were demonstrated advantages of such a system, such as a 15% reduction in fuel consumption and a significant reduction of harmful compounds emitted into the atmosphere (NO_x and CO by 25%). There were described all-electric and hybrid jet systems. The hybrid power of the aircraft's engines uses energy generated by a traditional turbine engine coupled to an alternator. Depending on the concept, this engine can only be used to generate electricity, such as APU (Auxiliary Power Unit), or it can generate extra thrust. Studies [19, 21, 22] also show the possibilities of using hybrid or distributed propulsions in passenger aircraft. Propulsions of this type would be based on a large fan motor providing part of the thrust, the remaining part would be generated by electrically driven fans or by distributed propulsion. Analyses are carried out regarding energy flow, fuel consumption and range compared to currently used flying vehicles. The significant impact of the new approach on reducing emissions of pollutants present in the exhausts is indicated.

Based on the research work analysed, it can be concluded that the use of hybrid or distributed propulsion can bring measurable benefits in the form of reduced energy or fuel consumption. However, such analyses would require experimental verification (CFD tests, energy flow modelling, determination of electricity consumption by fans – going into megawatts) and bench tests of propulsion system components. This could bring a broader view on the considered problems of air-propulsion development.

The application of distributed propulsion can significantly improve the performance of the aircraft. In [20], the authors presented a proposal for the use of distributed propulsion for a hybrid glider based on a hydrogen fuel cell. Calculations showed that it is possible to reduce hydrogen consumption by 3 kg, which will increase flight duration by 26.5%.

Based on the analysed research from various scientific centres, it can be concluded that conducting further focused research on pro-ecological solutions is justified and is not a temporary fashion but it falls under the '3E' paradigm.

3. Conclusions

Electric propulsions constitute a very interesting solution from the point of view of the attained aircraft performance in various flight conditions and the attained ecological properties. The characteristic of electric motors allows for more beneficial use of the propeller characteristics – it is easier to maintain the propeller within optimal parameters in terms of its efficiency during flight. In addition, the electric motor generates a lower level of vibration compared to the piston engine. This seemingly ideal propulsion also has its weaknesses. There remains a problem related to the range limited by the capacity of heavy batteries that do not provide a sufficient level of energy density to ensure the satisfactory range of the aircraft. For the same aircraft, the energy density in the hydrocarbon fuel (for the combustion propulsion variant built on the airframe) is two orders of magnitude higher than the one stored in batteries. In addition, the mass of the batteries reduces the payload of the aircraft and also reduces the range due to the aircraft's performance during the flight.

The hybrid propulsion is a transition phase before developing batteries with the appropriate energy density or efficient (lighter) fuel cells. However, it has a significant drawback, which is the complexity of the structure and the increase in the aircraft's take-off mass. There are also problems with ensuring the electromagnetic compatibility of complex high-energy systems making a fuel cell-based propulsion system. In the case of hybrid propulsion with a low degree of hybridization, there is a reduction in fuel consumption and exhaust as well as noise emissions, but the electric motor supports the internal combustion engine only at take-off or climb. An internal combustion engine is used during the cruise. Because of this and the flight characteristics of the aircraft (take-off and climb are relatively short stages of the flight), such systems seem to be not completely accurate for usage in aviation applications. The greater advantages of such a system could be seen in automotive applications where variability of rotational speed and engine load is often found, e.g. during city driving. For aviation applications, it seems advisable to use propulsions where the internal combustion engine drives the generator to recharge only the battery of the marching electric motor. This generator can be replaced by a fuel cell. Further work on hybrid and electric propulsion indicates that rather heavy and inefficient fuel cells will be the source of electricity for now, which will in time acquire sufficient features to ensure satisfactory aircraft performance.

Distributed propulsion can compensate for some of the disadvantages of electric propulsion by more efficiently managing energy on board, thereby ensuring greater range and duration of the flight. The same observation can also be made for hybrid propulsion, where the energy source is accumulators and a combustion generator or fuel cell. Previous studies carried out in various centres around the world as well as the authors' own research indicate that potential benefits of distributed propulsion should be sought in improving the aerodynamic parameters of the aircraft. Just selecting the propellers with a small diameter and the engines so that they run at their best efficiency parameters can result in lower energy consumption from its sources by a few percent. Only the forced acceleration of the air stream over the wing and thus increasing the lift coefficient (up to 4 times!) can bring measurable benefits for planning the power unit work strategy to minimize energy consumption, thereby increasing the range and duration of the flight.

The presented study indicates further research perspectives on the development of future propulsion for aviation falling under the 3E paradigm. The projections for development of distributed propulsion are promising. This type of propulsion can enable to increase efficiency and reduce fuel consumption, thereby reducing pollutants emissions in the exhausts and improving economic indicators. The development of this concept will be associated with a new approach to the design of flying vehicles as a transport system, and not a system of components with different functionalities.

Nomenclature

APU Auxiliary Power Unit
ATM Air Traffic Management
CAEP Committee on Aviation Environmental Protection
CFD Computational Fluid Dynamics
CO carbon monoxide
CO_2 carbon dioxide
C_z lift coefficient
E_{Bat} amount of energy stored in the battery
E_{Tot} total amount of energy stored on board the aircraft
H degree of hybridization
NO_x nitrogen oxides
ICAO International Civil Aviation Organization
NASA National Aeronautics and Space Administration
SESAR Single European Sky ATM Research programme
UAV unmanned aerial vehicle
ULD unit load device
VTOL Vertical Take Off and Landing

Aspect ratio: a measure of leaf slenderness expressed by the quotient of the flap length and its average geometrical chord

Degree of hybridization: the ratio of the amount of energy stored in batteries to the total amount of energy accumulated on board the aircraft

Distributed propulsion: the propulsion composed of a series of low-power thrust units located on the wing leading edge or on the fuselage

Energy density: the ratio of the amount of energy accumulated in the energy source to its mass

Flying wing: the structural system of an aircraft or glider without tail and not define a fuselage

Hybrid propulsion: a system using more than one energy source (e.g. battery and hydrocarbon fuel) to propel an aircraft or wheeled vehicle

Wing area: the surface of the projection of the aircraft's airfoil on a horizontal plane, giving the lift force

Wing loading: the ratio of the aircraft's mass (kg) to its wing area (m^2)

Wing span: distance between the wing ends of the aircraft

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