UDC 629.7.01
DOI: 10.15587/1729-4061.2020.212150

THE MODERNIZATION CONCEPT OF AIRCRAFT AN-26 AND AN-140 BASED ON THE USE OF A HYBRID POWER SYSTEM

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This paper reports a modernization concept of aircraft An-26 and An-140 based on the use of a hybrid basic propulsion system (HBPS). The study object is the aircraft of transport and passenger categories in the weight dimension from 20 to 25 tons. The analysis of the ways of modernization has shown that under the new market conditions two directions in the development of light aircraft «Antonov» become relevant. The first is the modernization of the existing fleet of An-26, the second is the construction of an An-140T ramp transport variant based on the An-140 aircraft. One of the considered ways of such modernization is to equip the aircraft with hybrid basic propulsion systems consisting of the gas-turbine and power electric motors, which drive the rotation of the propeller.

The use of HBPS makes it possible to optimize the operation of the gas-turbine engine over a narrow traction-speed range – only for the cruising section of the flight. This makes it possible to design a GTE with high fuel and weight efficiency. In this case, noise and harmful emissions could be significantly lower.

The analysis has been given of existing aviation hybrid propulsion systems with recommendations on the choice of the optimal scheme to modernize aircraft An-26 and An-140. It is proposed to solve the task by choosing the option of a basic propulsion system with a moderate degree of hybridization, based on the well-established engine TV3-117VMA-SBM1.

That improves the flight range of An-26 and An-140 with a payload capacity of 4.5–5 tons by 1.4–1.7 times, respectively.

The results obtained confirm the correctness of the proposed modernization concept. The analysis results demonstrate a significant improvement in the flight characteristics of the aircraft, as well as compliance with current and projected environmental standards. The results reported could be recommended for the practical modernization of aircraft An-26 and An-140

Keywords: modernization, hybrid basic propulsion system, rechargeable battery, control and switching tools

Received date 23.03.2020
Accepted date 09.09.2020
Published date 13.10.2020

1. Introduction

The cost of developing, certifying, and introducing newly created aircraft and aircraft engines ranges from hundreds of millions to several billion dollars. Therefore, for the recoupment of a modern aircraft project, it is necessary, at the initial stage of its implementation, to forecast the construction and introduction of various variants and modernization options of existing basic variants [1, 2].

A significant number of An-26 aircraft are in active operation; the resource of many of them allows their utilization over at least 15–20 years more. At the same time, the technical level of their onboard equipment is outdated and needs to be replaced. The construction of a new aircraft in this class requires considerable costs. It should also be taken into consideration that there is currently a competitive environment in the form of foreign light military transport aircraft (LMTA) S295, S-27J, and Il-112.

The An-140 light regional passenger aircraft is at the technical level of the late 1990s. The further development and construction on its base of the light ramp transport variant An-140T are possible only in the case of the deep modernization of assemblies and systems, with a simultaneous improvement in the technical-economic level.

In addition, research by Antonov State Enterprise (Ukraine) shows that the power of the existing engines from the family of TV3-117VMA-SBM1 is not enough to construct a competitive aircraft with a payload of about 5.5 tons. The use of technical solutions, such as putting aboard An-26 an additional turbojet engine, the type of RU-19A-300, reduces the weight perfection of the aircraft, its fuel efficiency, increases the noise level on the ground, and increases the emissions of harmful substances into the atmosphere.

One of the considered ways of modernization is to equip the aircraft An-26 and An-140 with hybrid basic propulsion systems (PS), consisting of the gas-turbine and power electric motor, which drives the rotation of the propeller [3]. This improves their performance and allows their operation under environmental constraints. The study results show a significant improvement in the flight characteristics of aircraft, as well as compliance with the current and projected environmental standards.

The scientific results obtained predict the prospects of such a direction, both for the perfection of the existing fleet of aircraft and in the design of new aircraft.

2. Literature review and problem statement

It is known that the hybrid engines of commercial aircraft are an area with great potential, allowing the improvement in fuel efficiency, reduced emissions of harmful substances, as well as reduced noise levels [4, 5].

Article [6] describes a solution to reduce harmful emissions and noise in the vicinity of airports in the category of regional passenger aircraft. The authors defined the specifications of aircraft and market requirements, which correspond to the actual sectors of air transport with the most appropriate introduction of all-electric or hybrid aircraft. Attention is paid to the development of regional aircraft with hybrid PSs. However, there are no quantitative indicators of the feasibility of the use of hybrid turboprop engines.

Paper [7] examines the current state of aviation engine engineering and the direction of works to construct critical technologies for promising aviation equipment abroad. It is shown that the turbofan engine (TFE) in the near future (the years of 2020...2025) will demonstrate the significantly improved parameters of the workflow and bypass ratio. The structure will widely exploit the composite materials in both the «cold» and «hot» parts of the engine. Over the medium- and long-term prospects (2030...2040), various concepts of aircraft with the hybrid (turboelectric) and electric propulsion systems are being considered, taking into consideration significant progress in the development of components of the electrical system [8]. The concepts of aircraft using components based on high-temperature superconductivity are also considered. However, the paper does not cover the issues of modernizing the existing aviation equipment in order to reduce the cost of one hour of flight.

In the nearest future, it is expected that the following areas of aircraft development will be important [7]: all-electric, hybrid (parallel hybrid, serial hybrid, parallel partial hybrid), and turbo-electric (all-turboelectric, partly turbo-electric). These six architectures are based on a variety of electrical technologies (battery, engines, generators, etc.). The cited work does not disclose the CO_2 emission reduction levels associated with different architectures, configurations, component characteristics, and tasks.

For regional aircraft and large aircraft, the structural configurations are typically divided into three categories: partially turbo-electric, all-turbo electric, and hybrid electric [9].

In all electrical systems, batteries are used as the only energy source aboard an aircraft. Hybrid systems use gas turbine engines to set in motion and to charge batteries; the batteries also provide energy to move during one or more stages of flight.

Studies [10, 11] explore the regional hybrid-electric aircraft powered by conventional gas turbines and battery-powered electric motors. Electric aircraft were investigated to test the operational strategies for hybrid propulsion systems. In particular, the role of batteries in the environmentally-friendly concepts with a significantly reduced carbon footprint was analyzed. The main findings underline the importance of choosing the right balance of battery power and energy in accordance with the flight cycle. However, the paper does not describe the ways to determine the technological feasibility of hybrid concepts.

Over the next 30 years, the same situation applies to technologies associated with superconducting engines and generators, fuel cells, and cryogenic fuels [12, 13]. For large commercial aircraft, it is likely that the use of fuel cells will be limited to auxiliary PS and launch systems. Over the next decade, alternative energy is expected to have a significant impact on emissions reductions and efficiency improvement while markets could be open for electrified small aircraft [14]. It is expected that after 2035, sustainable consumption of alternative fuels will become the norm for optimized gas turbines and alternative propulsion systems [15]. The issues of operating conditions for existing aircraft remain unresolved. It is not known how the requirements for existing power plants will change and whether there is a way to modernize them.

The ambitious climate goals set by the European Commission under the ACARE FlightPath 2050 program require significant improvements in the efficiency of future aircraft configurations [3, 16]. One of the main factors behind these improvements is the development of new PSs. Therefore, stakeholders in the aviation sector are increasingly interested in the concepts of electric engines because of their higher efficiency and reduction of harmful emissions. However, the introduction of such engines requires the rapid development of new technologies, which are currently difficult to implement. The use of a hybrid engine for a passenger aircraft may be an option to overcome the corresponding difficulties.

The assessment of the hybrid basic propulsion system configurations that exist in the world, described in papers [17–19], has made it possible to define the type of such installation for the current study.

Studies [20–22] provide information on the development of aircraft equipment with a hybrid basic propulsion system for aircraft whose take-off weight does not exceed 8,620 kg. This aviation equipment meets the requirements for the airworthiness standards FAR-23 or CS-23. Such aircraft have a mass of commercial load of no more than 2.5 tons. The development of new aircraft in a higher weight category and in the class of the airworthiness standards FAR-25 and CS-25 is currently constrained by a series of factors. First of all, there is no information on the practical development of hybrid aircraft propulsion systems with a capacity of 2,500 hp or more. In addition, the high cost of developing and certifying a new aircraft under the FAR-25 and CS-25 regulations is also a deterrent. Therefore, such studies are still purely theoretical, which is described in work [23] that reports the hypothetical aircraft in the dimension of ATR-72-600. Experimental work is also underway in this direction to construct a technology demonstrator [24, 25].

Thus, the scope of the research includes the development of the practical possibility of creating a transport aircraft with a hybrid basic propulsion system with a take-off weight of the aircraft of 20–25 tons.

An important aspect of work is the scope of aircraft modernization, which is supposed to be carried out relying on the already existing scientific, technical, and production base. In this case, significant funds are saved during mass production, and the time of implementation of structures is significantly reduced. The results obtained can be recommended for the practical modernization of aircraft An-26 and An-140.

3. The aim and objectives of the study

The aim of this study is to develop the modernization concept of aircraft An-26 and An-140 based on the use of a hybrid propulsion system.

To accomplish the aim, the following tasks have been set:

– to analyze existing hybrid basic propulsion systems and determine the possibility of constructing an aircraft with HBPS in Ukraine;

– to justify the modernization concept of aircraft An-26 and An-140 using a hybrid propulsion system based on an HBPS scheme;

– to demonstrate the feasibility of the energy balance of aircraft An-26 and An-140 and, as a result, show improvements in their flight performance.

4. Analysis of existing hybrid basic propulsion systems

The concept of a hybrid basic propulsion system (HBPS) implies the presence of a gas-turbine engine (GTE), a power electric motor (EM), an air propeller or fan, a rechargeable battery (RB), as well as control and switching tools.

The use of HBPS is currently being considered as part of a worldwide trend of increased interest in basic electric propulsion systems, primarily related to the tightened environmental restrictions on the release of harmful substances into the atmosphere.

The development of basic electric propulsion systems, in turn, depends on the progress in developing the electric motors themselves and increasing the charge density of rechargeable batteries.

Fig. 1 shows the sequence of stages in the development of basic electric propulsion systems in aviation by SAFRAN (France).

The studies [2, 3] of possible HBPS schemes with a capacity of 2,500 to 3,000 hp (1,850–2,250 kW), applied to the aircraft An-26 and An-140 under consideration, have resulted in two possible variants of their application: a consistent and parallel scheme.

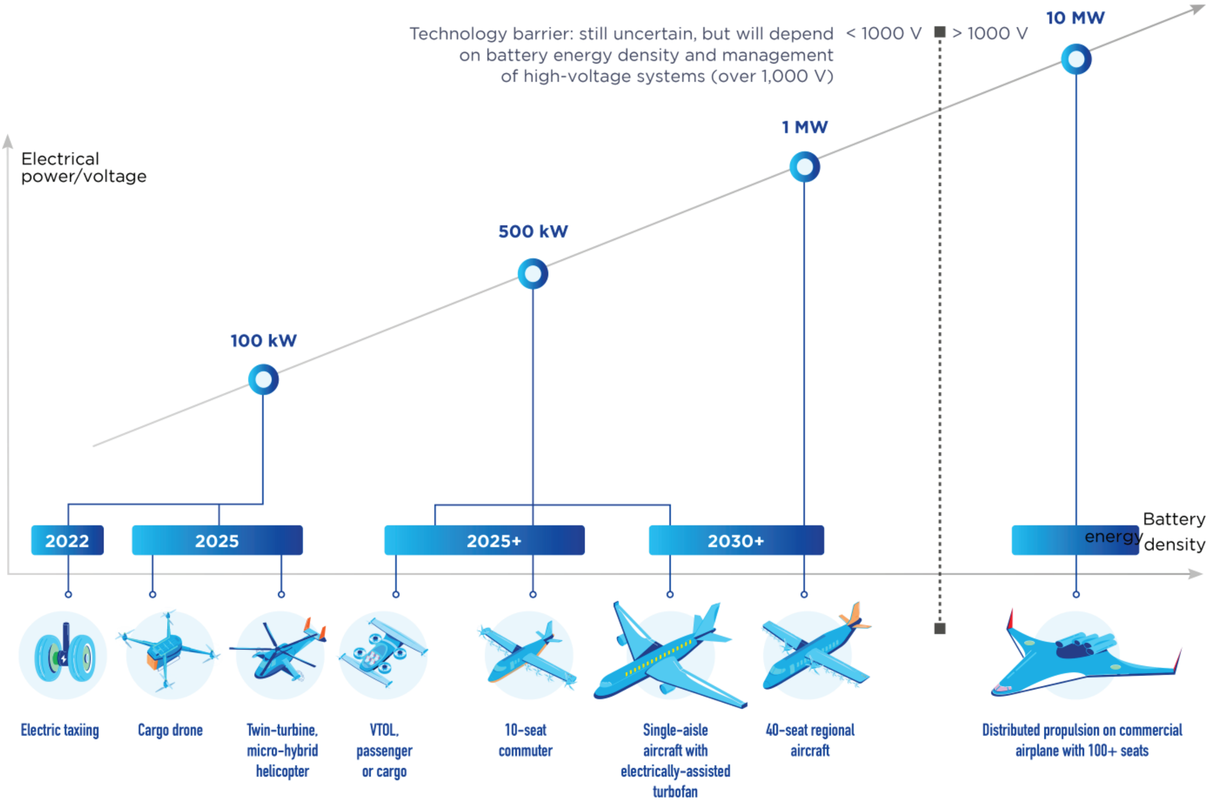

Fig. 1. The sequence of stages in the development of basic electric propulsion systems in aviation by SAFRAN

Variant I is a consistent scheme. The fundamental point in this scheme is that the direct drive of the engine, an air propeller or fan, is operated by an electric motor only. The electric motor at almost all stages of the flight is powered by GTE, which is essentially single-mode and activates the electric generator (or generators). This makes it possible to use the TTD specifically optimized for the specified conditions, thereby minimizing its size, mass, fuel consumption, and increasing the resource. The rechargeable battery is, in this case, used as an electricity buffer and to power EM in an emergency. This makes it possible to minimize its capacity, respectively, the size, mass, and price.

An example of the use of such a scheme is the HBPS in the Zunum Aerohybrid-electric small regional aircraft project, designed overseas and partly financed by Boeing [17, 18].

The light passenger 12-seater aircraft ZA01 (Fig. 2) is designed for a range of up to 700 miles (about 1,130 km). The direct drivers in this project are two ducted fans mounted on the sides of the fuselage, which are powered by 500 kW electric motors. A single modified Ardident 3 turbo engine with a capacity of 1,700 hp by Safran is planned as a turbo generator.

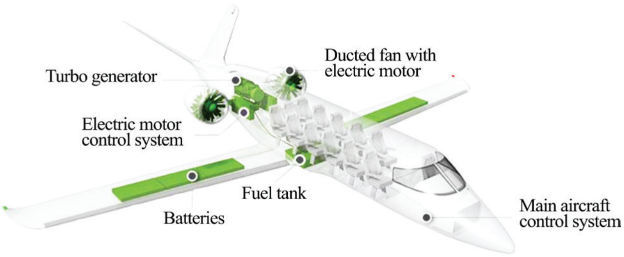

Fig. 2. The aircraft Zunum Aero ZA-1 project with an HBPS [24]

The degree of progress of the program is evidenced by the fact that Safran has already conducted ground tests of the 500 kW turbo generator demonstration variant in 2019 to be installed in conjunction with a ducted fan at the Rockwell Turbo Commander flying laboratory, instead of the left turboprop engine.

Flight tests are expected soon.

Variant II is a parallel scheme. The fundamental point in this scheme, Fig. 3, is that the GTE and EM drive the engine jointly (parallelly) through the common gearbox. This scheme also implies a separate drive of the engine. For example, the air propeller is driven by the GTE, and, at the same time, the EM is used as a generator to charge the batteries using part of the mechanical power of the GTE. The EM is used under a power mode only on the regimes of maximum power required – take-off, departure on the second lap, or a set of height. The main advantage of a given scheme is the possibility to reduce the power dimensionality of both the GTE and EM, thereby reducing their mass-size parameters, as well as the degree of technical risk and cost indicators.

Project 804 by the United Technologies Corp. (UTC) in the United States [19] is a good example of the use of the parallel HBPS scheme, which is promoted in conjunction with Pratt & Whitney Canada and Rockwell Collins. The project is the modified passenger 39-seater aircraft for the local airlines, Bombardier Dash 8 Q100 (Fig. 4). The aircraft is equipped with two HBPSs with a total capacity of 2,720 hp (2 MW) each. In this case, the ratio between the GTD and EM is equal and is 1,360 hp (1 MW) [19]. It is planned to place rechargeable batteries and control and switching tools under the floor of the passenger cabin. According to the developer company UTC, the use of hybrid technologies could reduce fuel costs by up to 30 % for routes with a range of 370–460 km. A demonstrator plane is expected to fly in 2022.

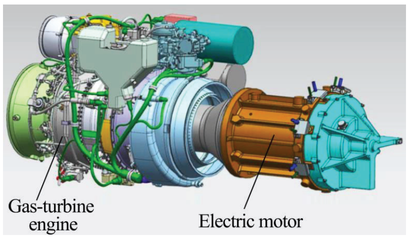

Fig. 3. The concept of HBPS in a parallel scheme with a power of 1 MV by Honeywell [9]

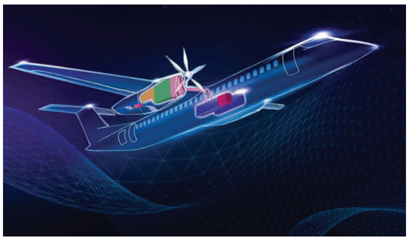

Fig. 4. Project 804 is promoted by the UTC Corp. [19]

One of the important issues of practical implementation of the use of HBPS on an aircraft is the optimal layout of the placement of rechargeable batteries and control and switching tools, minimizing the length of power cables. That could reduce weight, improve the system's efficiency and fire safety. For example, one such variant, using the modified passenger aircraft ATR-72-600 as an example of (Fig. 5), is that the rechargeable battery can be placed in the center section of the wing [23].

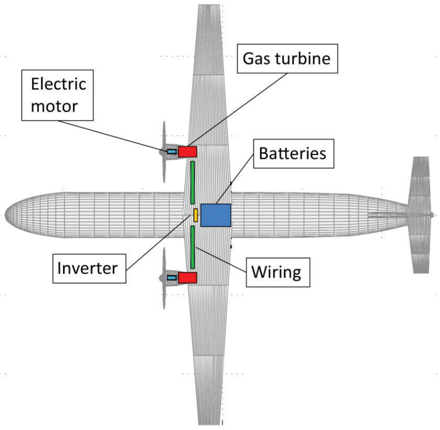

Fig. 5. The hypothetical layout of the main components of HBPS based on the passenger aircraft ATR-42-600 [23]

This could minimize the length of the wiring and remove it from the passenger cabin area and the BREO electric cables and aircraft control systems and lines of the aircraft's control system. Such a solution would make it much easier to certify the aircraft in accordance with the requirements for failure-free operation.

There are currently several programs in the world related to the use of HBPS on aircraft. Of the greatest interest among them is the work of the Airbus corporation and information on the construction of a light transport aircraft equipped with HBPS for the Brazilian Air Force, which is carried out by the Brazilian startup Desaer, founded by former specialists from Embraer.

The Airbus concern, as part of the creation of aircraft with HBPS, is working on the construction of a hybrid demonstrator aircraft Airbus E-Fan X [24] based on the regional passenger aircraft BAe-146 (Fig. 6). This is a joint project of Airbus, Rolls-Royce Siemens. The first flight of the experimental aircraft is scheduled for 2020.

The main stated characteristics of the Airbus E-Fan X:

– Siemens SP2000 2MW liquid-cooled propulsion electric motors;

– a 2.5 MW generator;

– a 3,000 V network voltage;

– a rechargeable battery power of 2 MWh;

– a loss of power on the generator and engine is 15 %.

At the end of December 2019, it was announced [25] that Embraer had signed a memorandum with the Brazilian Air Force (Forca Aerea Brasileira, or FAB) about its intention to construct a light twin-engine, four-engine, ramp transport aircraft with HBPS for operation in the depths of Brazil. No detailed official data on the technical task on the aircraft were made public but it is known that it must have a payload capacity of at least 3,000 kg and be operated from unpaved airfields, 1,200 m long.

It is likely that this project may be based on the development of a light twin-engine ramp transport-passenger aircraft ATL-100 (Fig. 7), developed by the Brazilian start-up Desaer. The aircraft is designed to carry 19 passengers or cargo weighing up to 3,000 kg from short unpaved runways, 1,200 m long. The aircraft must provide transportation of LD-3 containers, parachute dropping of pallets with cargo and medical equipment, transportation of military personnel and wounded, dropping of parachutists. Based on the payload capacity, it can be concluded that it is planned to be certified in accordance with the standards of airworthiness FAR-23, and its take-off weight will be limited to the size of 19,000 pounds or 8,618 kg.

Fig. 7. Preliminary general view of the Desaer ATL-100 aircraft [20]

According to the information for mid-2019, it was assumed that the first ATL-100 would take to the air in 2021, and the completion of its certification was expected at the end of 2023. In the initial version, the ATL-100 aircraft was planned to be equipped with a conventional gas-turbine MDU based on the RT-6 engines, and its version with the HBPS was considered as a further development of the aircraft.

In addition, information appeared about plans to create a hybrid power plant by General Electric based on a 1,300 hp gas turbine engine [22].

Fig. 6. Experimental aircraft with HBPS Airbus E-Fan X [24]

Thus, under the current conditions of aviation development in the world, the construction of HBPS in Ukraine is possible in cooperation with the world's leading manufacturers of electric motors, rechargeable batteries, electrical equipment, and air propellers. At the same time, the domestic industry has the potential to implement this idea in practice.

In Ukraine, there are the following enterprises that may be involved in this process:

– Antonov State Enterprise is a project integrator, equipping an aircraft with a hybrid propulsion system, flight and certification tests, and mass production (or alteration from an existing aircraft), after-sales maintenance;

– Ivchenko-Progress ZMKB – the development and modernization of the gas-turbine propulsion system, as well as the construction of an air propeller;

– JSC Motor Sich – the mass production and after-sales maintenance of the gas-turbine power plant;

– Kharkiv Assembly Design Bureau (KADB) – the development and manufacture of a valved engine.

The following companies may become potential foreign partners in the project:

– MT-Propeller Entwicklung GmbH (Germany) – the development and manufacture of air propellers and regulators to them;

– Aerospace Technology Centre Innovation Park, The University of Nottingham (UK) is a scientific and technological partner in the development and manufacture of hybrid and electric propulsion systems;

– MagniX (USA/Australia) is a developer and manufacturer of aircraft electric engines.

5. The concept of modernizing aircraft An-26 and An-140 using a hybrid propulsion system

Consider the choice of an HBPS scheme for the An-140/An-26 E-hybrid aircraft. When choosing the optimal scheme of the HBPS and the degree of its «hybridization», we analyzed [3] and solved the following tasks:

– practical «feasibility» of the scheme based on the current state of the development of RB and aviation electric drives;

– minimizing the weight and dimensions of the design;

– maximizing the fuel efficiency of HBPS using existing components.

The following structural solutions for HBPS were considered during the development process:

– with the electrical transmission of energy from the GTE with the transmission of power only from the electric motor to the engine shaft (consistent scheme);

– with a parallel transmission of power from the GTE and the electric motor to the common engine.

In all variants, we considered a multi-bladed air propeller as the engine. The supply of electric energy, as well as its buffering, is provided by a modular Li-ion RB.

Variant I includes the electrical transmission of energy from the GTE with power transmission only from the electric motor to the engine shaft (Fig. 8).

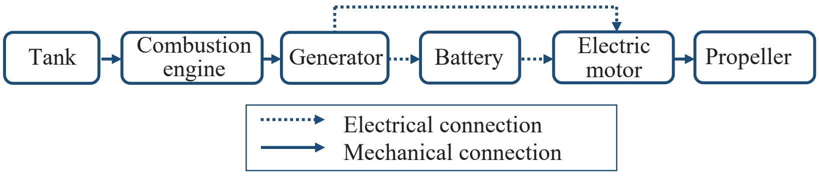

Fig. 8. An example of using a sequential HBPS scheme

Advantages:

– the possibility of placing a «separate» power unit based on a gas-turbine engine, anywhere in the aircraft, including in the contours of the fuselage. At the same time, the mass-dimensional parameters of the power unit can be much larger than in any other version;

– the possibility to optimize the thermodynamic processes of the GTE, in order to ensure minimum fuel consumption and emissions of harmful substances (including the use of heat recovery);

– the possibility to accumulate the entire flow of electric energy in an RB, in order to perform a takeoff with «zero» emissions of harmful substances.

Disadvantages:

– the need to have an electric motor at «full» take-off capacity (which would require a complex cooling system, as well as bulky and heavy electrical distribution equipment);

– to accumulate the entire flow of electricity, a large capacity RB is required, and, therefore, mass and size;

– the need for a separate generator on the power hub, designed for its full power or cruising power, which would increase the overall weight of the power plant.

Variant II includes a parallel transmission of power from the GTE and electric motor to the common engine (air propeller) through a single drive (reducer), shown in Fig. 9.

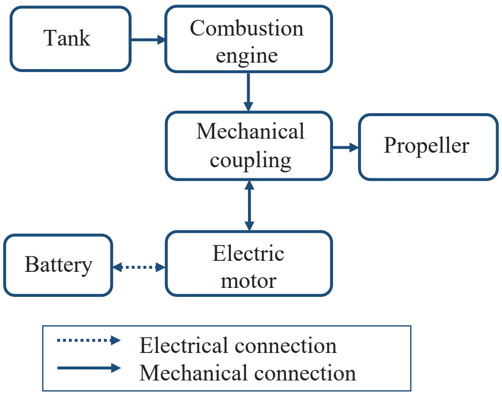

Fig. 9. An example of using a parallel HBPS scheme

Advantages:

– the possibility to reduce the mass of the PS by combining «all» mechanical drives in a common gearbox and excluding a separate generator, to charge the RB (a valved engine is an inverse machine and can operate in the mode of generating electricity);

– the possibility to ensure that the GTE operates under an optimal mode, in order to ensure minimum fuel consumption (for a given design);

– there is no need to use an electric engine at full capacity of the PS as the electric motor is used in a booster mode (adding the missing power at certain flight modes);

– there is no need to use a large capacity RB (battery capacity is determined by the duration of booster modes);

– the possibility of constructing a PS based on the existing turboprop engine (TPE) structures TV3-117VMA-SBM1, developed by the industry of Ukraine.

Advantages:

– the impossibility of implementing the take-off of the aircraft with a «zero» emission;

– the difficulty of constructing GTE with heat recovery at acceptable mass-size indicators;

– the complexity of the layout of a PS in a single assembly;

Based on the above analysis and given the practical feasibility of the project, the second variant with a moderate degree of hybridization was chosen – an electric motor is used for a take-off mode, altitude gain, and a go-around flight maneuver. In this case, during the flight, there is a charge of the RB from the electric motor operating in a generator mode.

5. 1. HBPS application on aircraft An-26

Fig. 10 shows a preliminary assessment of the construction of an HBPS based on the gas-turbine engine TV3-117VMA-SBM1 and the electric motor MagniX (USA/Australia) with a 6-bladed air propeller with a diameter of 3.9 m, made by MT-Propeller Entwicklung GmbH (Germany), on aircraft AN-26 and AN-140T.

The HBPS concept adopted at this stage implies the use of the upgraded TV3-117VMA-SBM1 engine.

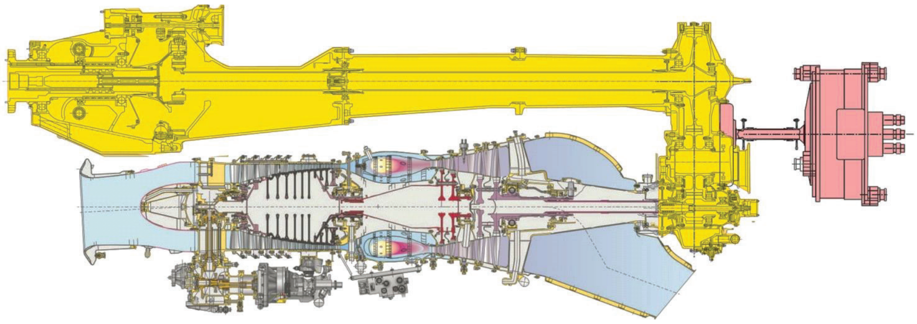

Fig. 10. Preliminary HBPS scheme based on the engine TV3-117VMA-SBM1 (the scheme by Ivchenko-Progress ZMKB)

The design features of the engine make it possible to solve the task of transferring power from the electric motor to the propeller at minimal refinement. The increased propeller capacity, in comparison with the original PS, requires the use of 6-bladed propellers with a diameter of at least 3.9 m, against the air propeller AV-140 with a diameter of 3.73 m, used on aircraft AN-140.

The structural-power integration of TPE and EM into a single energy node and its arrangement under the wing of the aircraft requires additional work. One of the issues that complicate the implementation of the installation of the TV3-117VMA-SBM1 engine on the AN-26 is the organization of the release of its exhaust jet in such a way as to preserve the aircraft's chassis and make the most of the elements of the existing nacelle.

Preliminary studies show that the optimal variant may be to organize an exhaust bypassing the chassis wheel on both sides (Fig. 11). This would require the modification of the engine exhaust system.

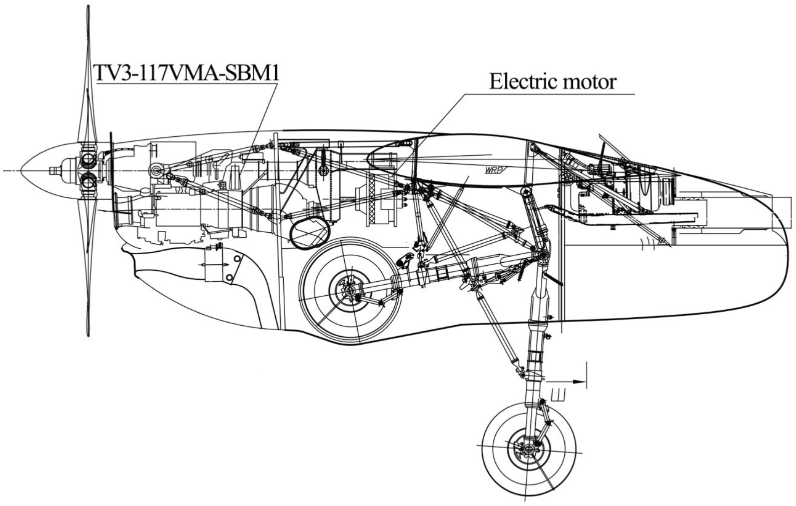

Fig. 11. Preliminary scheme of a hybrid basic propulsion system on the An-26 aircraft (the scheme by Antonov State Enterprise)

The use of Magni electric motors with a liquid cooling system would require the use of additional elements – heat exchangers and radiators, which make it possible to maintain the thermal balance of both the electric motor under different modes and the rechargeable batteries pack.

A power supply system will be fundamentally new on the plane. Our analysis of other energy-dependent systems has revealed that the aircraft's de-icing protection would need to be upgraded to replace the air-thermal tail systems with an electric thermal one and the elimination of air-thermal protection for the engine intake.

A preliminary scheme of the general view of An-26 with a hybrid basic propulsion system is shown in Fig. 12.

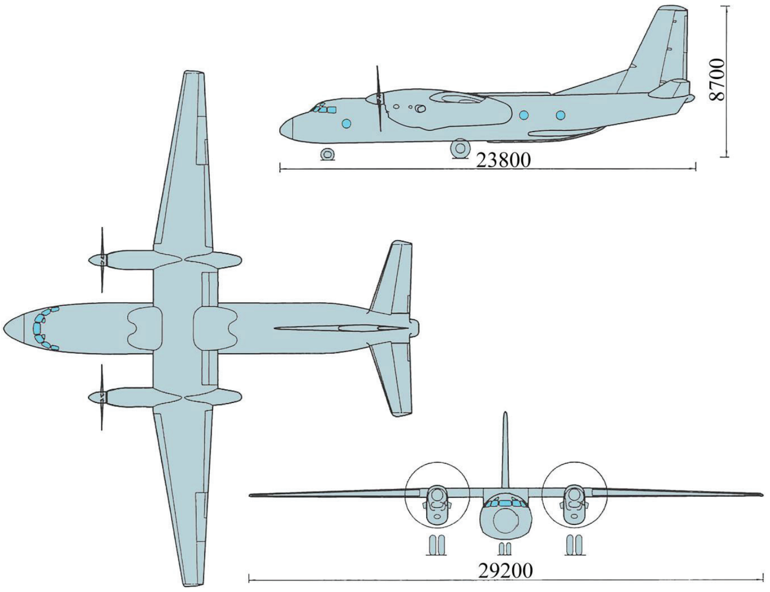

Fig. 12. Preliminary scheme of the general view of An-26 with a hybrid basic propulsion system (the scheme by Antonov State Enterprise)

5. 1. 1. Energy balance of the power plant of the An-26 aircraft

1. A new HBPS consisting of two gas-turbine engines TV3-117VMA-SBM1 (a take-off capacity of 2,500 hp, Extraordinary Mode – 2,800 hp) and two electric motors (max. capacity of 285 hp (209 kW) is installed, driving the propeller into rotation through a common gearbox.

The ideology of joint use of both types of engines at different stages of flight:

– the gas-turbine engines operate during takeoff, climb, cruise, descent, and landing under appropriate operating modes;

– electric motors act as auxiliary engines and operate during take-off stages (two electric motors at 100 % power), continued takeoff (one electric motor at 95 % power), and altitude mode (65 % power). At cruising flight and descent, the electric motor operates in a generator mode, charging the rechargeable batteries;

– the landing phase and, if necessary, the aircraft's go-around flight maneuver involves both engines.

2. Operation time of electric motors at take-off and climbing:

– take-off is 3 minutes (0.05 hours);

– climbing is 26 minutes (0.42 hours).

Total: 29 min or 0.47 hour.

3. For a full-time takeoff, the required capacity of 5,570 hp (similar to An-26, 2×AI-24VT for 2,500 hp, plus 1×RU-19 with a thrust of 650 kgf (equiv. 570 hp) is enabled by four engines – 2 gas-turbine engines TV3-117 and 2 electric motors:

5,570 hp=2×2,500 hp (GTE)+2×285 hp (EM, 2×209 kW).

For climbing, the required capacity of 4,570 hp (similar to An-26, 2×AI-24VT of 2,000 hp, plus 1×RU-19, with a thrust of 650 kgf) is enabled by four engines – 2 gas-turbine engines TV3-117 and 2 electric motors:

4,570 hp=2×2,100 hp (GTE)+2×185 hp (EM, 2×136 kW).

For takeoff with a failed engine, the required power of 3,070 hp (similar to AN-26, 1×AI-24VT of 2,500 hp, plus 1×RU-19 with a thrust of 650 kgf) is provided by two engines – 1 gas-turbine engine TV3-117 and 1 electric motor:

3,070 hp=1×2,800 hp (GTE)+1×270 hp (EM, 1×198 kW).

4. The energy required to operate the electric motors in the event of engine failure at the end of climbing with a go-around flight maneuver at landing (the most difficult case):

– take-off within 0.05 hours: 2×209 kW×0.05 h=21 kWh;

– climbing within 0.42 hours: 2×136 kW×0.42=113 kWh;

– a go-around flight maneuver within 0.1 hours: 1×198 kW××0.1=20 kWh

21 kWh+113 kWh+20 kWh=154 kWh.

Thus, the aircraft should be fitted with an RB with a total capacity of 154 kWh.

5. The weight of the RB at a specific capacity of RB of 0.35 kWh/kg will equal 154/0.35=440 (kg).

The volume of RB at a specific RB capacity of 0.5 kWh/l will equal 154/0.5=308 (l).

6. At the cruising section of the flight with a duration of 2.5 hours (5.5 tons per 1,000 km), due to the excess available power of two GTEs, the batteries can be charged to 200 kWh, 100 kWh for each EM, which is even larger than the apparent capacity of the RB.

7. Two electric motors require approximately 20 kWh of electricity when the aircraft executes a go-around flight maneuver, which is much less than the capacity of the RB charged to 154 kWh. Consider the weight balance, Table 1 gives the comparative weight balance of the power plant of the standard aircraft An-26 and its modification with the HBPS – the An-26-E aircraft.

Table 2 gives the basic flight and technical characteristics for two variants of the aircraft: An-26 with a standard basic propulsion system and An-26-E with HBPS. In this case, the characteristics of the An-26 correspond to Flight Manual. Fig. 13 shows a «Cargo-Range» diagram of aircraft An-26 and An-26-E.

Table 1

Comparative characteristics of power plants

HBPS, based on TV3-117	Mass, kg	Standard basic propulsion system, based on AI-24+RU-19-300	Mass, kg
HBPS, including: 2×TV3-117VMA-SBM1, auxiliary power unit AI9-3B, electric motors, rechargeable batteries, cooling and switching	3,953	Standard basic propulsion system, including 2×AI-24VT, auxiliary power unit RU-19-300	3,612
Air propellers AV-140	420	Air propellers AV-72	708
Nacelles, exhaust system, engine mounts, aircraft units, basic propulsion system control, oil system and oil, refinement of basic propulsion system to HBPS	1,079	Nacelles, exhaust system, engine mounts, aircraft units, basic propulsion system control, oil system and oil	1,341
TOTAL:	5,452		5,661

Table 2

Comparative characteristics of aircraft

Aircraft	AN-26	AN-26-E
Maximal take-off weight, t	24.0	24.0
Maximal payload, t	5.5	5.5
Mass of empty equipped aircraft, t	16.3	16.64
Maximal fuel reserve (=0.81), kg	5,500	5,500
Engines:		
– type TPE	AI-24VT+RU19	TV3-117VMA-SBM1+electric motor
– power, hp +RU-19A-300 or electric motor	2×2,500+800 kgf	2×2,500 (2800- Extraordinary Mode)+600 kgf
Cruise speed, km/h	400–440	400–440
Cruise altitude, m	5,000–6,600	5,000–6,600
Practical range (emergency reserve fuel=580 kg), km:		
– with 5.5 t	541	765
– with 4.56 t (38 soldiers×120 kg)	1,020	1,418
– with maximal fuel reserve (cargo, t)	2,236 (2.2)	3,364 (6)
– without cargo	2,415	3,474
Kilometer voyage fuel consumption at max. load, kg/km	2.82	1.67
Fuel efficiency at max. load, g/t km	543	304
Cruising aerodynamic quality *K*, (M=0.5; C_y=0.5)	11.36	11.28

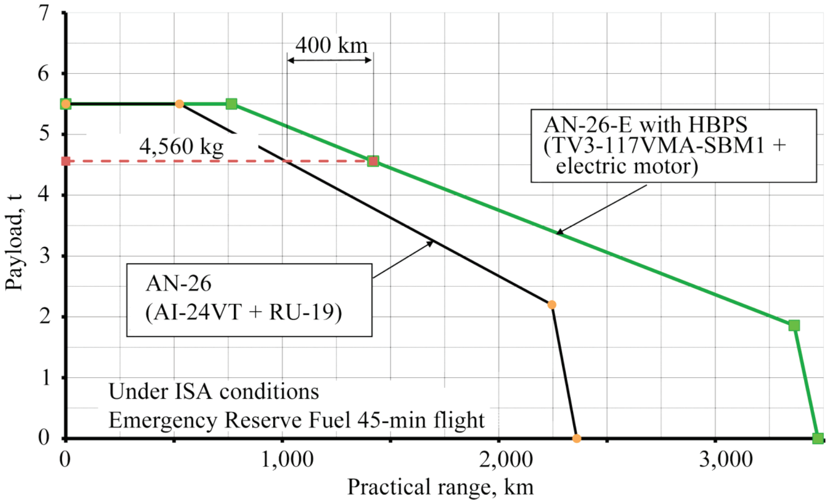

Fig. 13. Comparative «cargo-range» diagram of An-26 and An-26-E aircraft with HBPS (the scheme by Antonov State Enterprise)

Based on our assessment, it can be concluded that the use of HBPS on the An-26 aircraft increases the range of flight. In this case, when performing a typical tactical task of transporting 4,560 kg of cargo, the range increases by 400 km. For the case of a flight with 2 tons of cargo (a possible variant of the aircraft with special equipment), the range increases by more than 1,100 km and the flight duration – by more than 2 hours.

5. 2. HBPS application on the An-140T aircraft

The HBPS concept adopted in this case is similar to that of the AN-26E aircraft and implies the use of an upgraded TV3-117VMA-SBM1 engine with an upgraded gearbox. The increased propeller capacity, compared to the original PS, requires the use of 6 bladed propellers with a diameter of at least 3.9 m, against the previously used air propellers AV-140 with a diameter of 3.73 m.

The issues of the structural-force integration of TPE and EM into a single energy node and its arrangement under the wing of the aircraft, in this case, are generally identical to those previously considered for the aircraft AN-26E.

It will also require a modification of the engine exhaust system in connection with the installation of an electric motor behind the TPE (Fig. 14). The use of Magni electric motors with a liquid cooling system will require the use of additional elements – heat exchangers and radiators. They will make it possible to maintain the thermal balance of both the electric motor directly at different modes of operation (a power mode or generator mode) and a pack of rechargeable batteries. The latter demands strict adherence to the temperature regime.

The preliminary layout of such PS is shown in Fig. 15.

A power supply system will be fundamentally new on the plane. Analysis of other energy-dependent systems has shown that they would require little or no significant change.

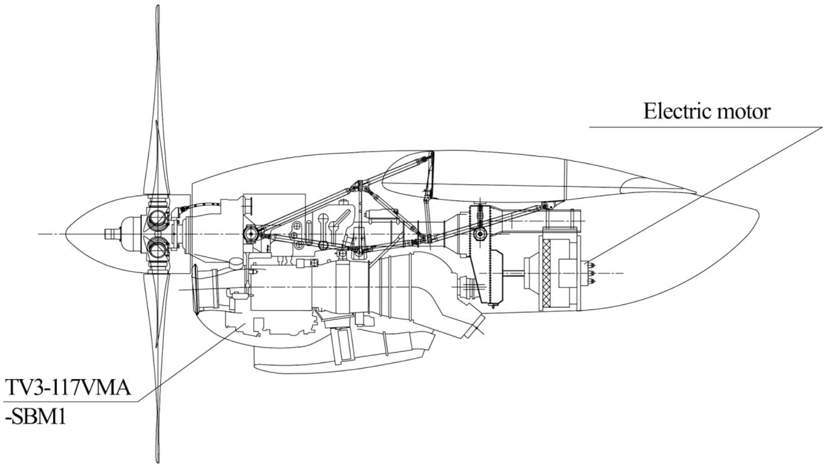

Fig. 14. Preliminary scheme of the hybrid basic propulsion system on an AN-140T aircraft (the scheme by Antonov State Enterprise)

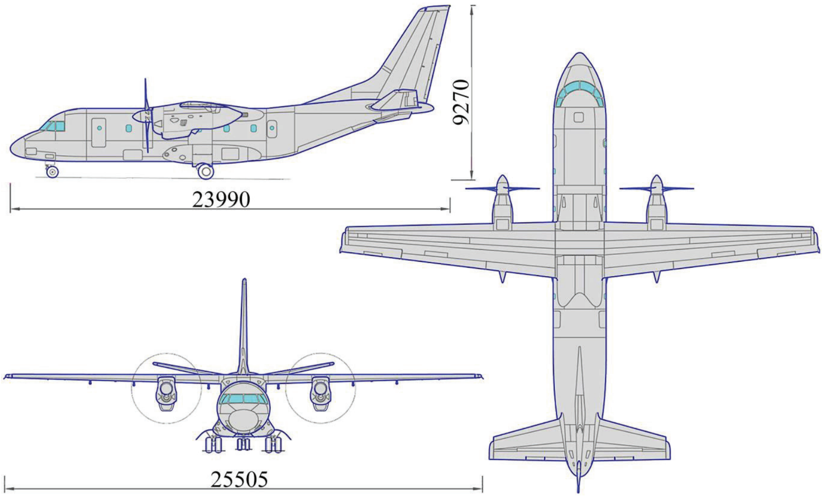

Fig. 15. Preliminary scheme of the general view of AN-140T with a hybrid basic propulsion system (the scheme by Antonov State Enterprise)

5. 2. 1. Energy balance of the power plant of the AN-140T aircraft

1. The aircraft is fitted with an HBPS consisting of 2 gas-turbine engines TV3-117VMA-SBM1 (a take-off capacity of 2,500 hp, Extraordinary Mode – 2,800 hp) and 2 EMs (maximum capacity of 285 hp (209 kW), which rotate the AV-14H ($D_{propeller}$=3.93 m) air propeller through the common gearbox.

The ideology of joint use of both types of engines at different stages of flight:

– the gas-turbine engines operate at the stages of take-off, climbing, cruising, descent, and landing under the respective modes of operation;

– the electric motors act as auxiliary engines and operate in the take-off (two EMs at 100 % capacity), continued take-off (one EM at 100 % capacity), and climbing mode (50 % capacity) stages. At cruising and descent, the electric motor operates in a generator mode, charging the rechargeable batteries;

– the landing phase and, if necessary, the aircraft's go-around flight maneuver involve both engines.

2. The operation time of electric motors on take-off and climbing:

– take-off – 3 min (0.05 hour);

– climbing – 25 min (0.42 hour).

Total: 28 min or 0.47 hour.

3. For a full-time takeoff, the required capacity of 5,400 hp is provided by four engines – 2 gas-turbine engines TV3-117VMA-SBM1 and 2 EMs:

5,400 hp=2×2,500 hp (GTE)+2×200 hp (EM, 2×147 kW).

For climbing, the required capacity of 4,600 hp (similar to An-140T, 2 TV3-117VMA-SBM1×2,350 hp) is provided by four engines – 2 gas-turbine engines TV3-117VMA-SBM1 and 2 EMs:

4,650 hp=2×2,100 hp (GTE)+2×200 hp (EM, 2×147 kW).

For takeoff with a failed engine, the required power of 3,085 hp is provided by two engines – 1 gas-turbine engine TV3-117VMA-SBM1 and 1 EM:

3,085 hp=1×2,800 hp (GTE)+1×285 hp (EM, 1×209 kW).

4. The energy required to operate the electric motors in the event of engine failure at the end of climbing with a go-around flight maneuver at landing (the most difficult case):

– a take-off within 0.05 hour: 2×147 kWh×0/05 h=15 kWh;

– climbing – 0.42 hour: 2×147 kW×0.42 hour=123 kWh;

– a go-around flight maneuver – 0.1 hours: 1×285 kW××0.1 hour=29 kWh.

15 kWh+123 kWh+29 kWh= 167 kWh

Thus, the RB with a total capacity of 167 kWh should be installed on the aircraft.

5. The weight of the RB at a specific RB capacity of 0.35 kWh/kg will be 167/0.37=477 kg.

The RB volume at the specific RB capacity of 0.5 kWh/l equals 167/0.5=334 l.

Table 3 gives the basic flight and technical characteristics for two variants of the An-140T aircraft – with a regular propulsion system of two basic propulsion engines TV3-117VMA-SBM1 and a variant of An-140T-E with HBPS, as well as, for comparison, the flight and technical characteristics of a standard passenger aircraft An-140-100.

Table 3

Comparative characteristics of aircraft

Aircraft	AN-140-100	AN-140T	AN-140T-E
Engines:			
– type	ТВ3-117ВМА-СБМ1	ТВ3-117ВМА-СБМ1	ТВ3-117ВМА-СБМ
– take-off power, hp	2×2,500/2,800	2×2,500/2,800	2×2,500/2,800+electric motor 2×285 hp
Take-off mass, t	21,5	21,0	23,15
Mass of empty equipped, t	13,43	13,80	14,50
$K_{cruising}$ (0.45; 0.5)	12,9	11,95	11,95
Maximal payload, t	6,0	6,0	7,5
Maximal fuel reserve, t	4,68	4,68	4,68
Cruise speed, KM/h	450	450	450
Cruise altitude, km	5,800–6,600	6,000	5,500–6,400
Max. cruise speed, KM/h	470	470	470
Emergency Reserve Fuel, min (at a circle altitude)	45	45	45
Practical flight range, KM:			
– with a cargo of 7.5 t	–	–	470
– with a cargo of 6 t	1,225	500	1,580
– with a cargo of 5 t	2,080	1,330	2,380
– at max. fuel reserve (cargo, t)	3,390 (3.44)	3,260 (2.57)	3,040 (12)
– without cargo	3,700	3,580	3,570
Mean voyage fuel consumption at 6-ton cargo:			
– g/t-km	221	245	239
– kg/km	1.35	1.58	1.46
– kg/h	564	579	615

Fig. 16 shows a comparative «Cargo-Range» diagram for aircraft AN-140-100, AN-140T, and AN-140T-E.

Based on our assessment, it can be concluded that the use of HBPS on the An-140T aircraft significantly increases the range of flight.

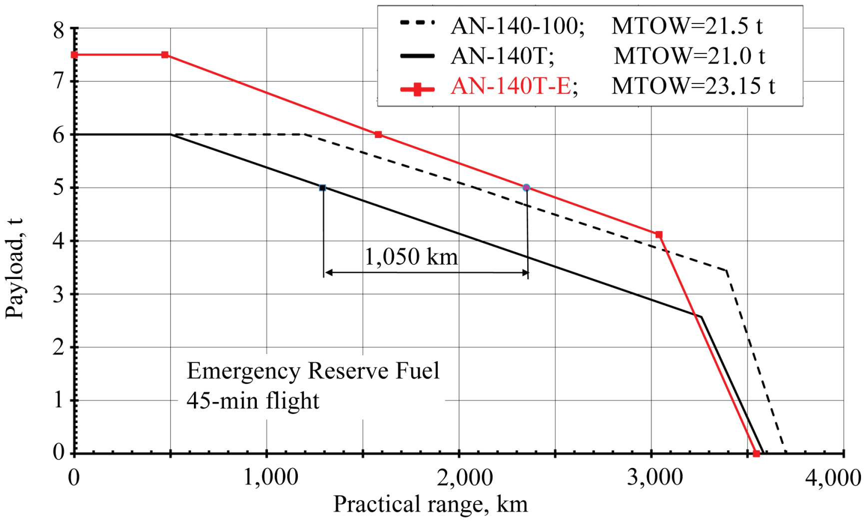

Fig. 16. Comparative diagram «cargo-range» for various variants of the An-140 aircraft, including the AN-140T-E variant with HBPS (the scheme by Antonov State Enterprise)

In this case, the range increases by 1,050 km when performing a typical tactical task of transporting 5 tons.

6. Discussion of the results of studying the possibility of the modernization of aircraft An-26 and An-140

The reported results of the improvement in the aircraft flight characteristics (Fig. 13, 16) and their fuel efficiency indicators (Tables 2, 3) are primarily explained by the use of the optimal modes of operation of the gas-turbine engines. This reduces fuel consumption and, accordingly, reduces the emissions of pollutants into the atmosphere. The improved fuel efficiency, by up to 56 % (from 543 g/t km to 304 g/t km), is most noticeable for the An-26 aircraft.

As of now, there are no practically implemented projects to construct the aircraft of the weight size of An-26 and An-140, equipped with HBPS. In comparison with theoretical projects, for example, the project to construct a passenger aircraft of the ATR-72-600 class [8] implies the use of rechargeable batteries with a significantly larger specific capacity.

The current study is preliminary and limited to the mass-produced and well-developed production by the Antonov State Enterprise – aircraft An-26 and An-140.

Given the impossibility of calculating at this stage the quantitative indicators of noise and other environmental indicators, set by international documents, this paper has considered those indicators that demonstrate the improved fuel efficiency.

Detailed research implies a deeper design of elements, both the power plant, rechargeable batteries, power electrical wiring, and an aircraft frame with systems, which could lead to changes in the technical and mass indicators.

7. Conclusions

1. We have analyzed existing hybrid basic propulsion systems, the use of which improves the technical and economic level of an aircraft and significantly reduces harmful emissions, especially CO_2. The concept of modernization of the An-26 and An-140 airplanes based on the use of a hybrid power plant with a choice of the HBPS scheme has been developed and substantiated. The domestic hybrid power plant is based on the TV3-117VMA-SBM1 engine.

2. The concept of the use and the scheme of an HBPS for the AN-140/AN-26 E-hybrid aircraft have been substantiated.

When choosing the optimal scheme of HBPS and the degree of its «hybridization», we have analyzed the practical «implementation» of the scheme, minimizing the weight and dimensions of the structure, as well as the maximum fuel efficiency of the HBPS. In the process of developing the concept, structural solutions for the HBPS with consistent and parallel energy transmission schemes have been analyzed.

3. The feasibility of the energy balance for both aircraft and the possibility of improving their flight and technical characteristics have been demonstrated. An analysis of the energy-dependent systems of the An-26 aircraft has been carried out.

In this case, the range of flight with a cargo of 4,560 kg increases by 400 km, and with a cargo of 2,000 kg – by 1,000 km. The analysis of the energy-dependent systems of the An-140 aircraft was carried out when creating its ramp cargo version. It is shown that the use of the domestic HBPS in the execution of a typical tactical task of transporting a cargo of 5,000 kg yields an increase in the range of flight by 1,050 km.

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