ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

UDC 621.452.3.022-732:504.054 **doi: 10.32620/aktt.2024.1.01**

Ruslan TSUKANOV, Sergii YEPIFANOV

National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine

ANALYSIS OF ENVIRONMENTALLY FRIENDLY COMMERCIAL AVIATION DEVELOPMENT WAYS

*The **goal** of this study is to identify effective directions to decrease the greenhouse gas emissions of commercial aviation. The **subject matter** of this research is to analyze ways known from literature to decrease the greenhouse gas emissions of commercial aviation: continued evolution (which includes a lot of various methods for partial reduction of greenhouse gas emissions with decreasing in fuel consumption), «net zero» (which includes the following methods: offsets and sustainable aviation fuel utilization), electric hybrid power plants (parallel, series, series/parallel, turboelectric, and partial turboelectric), «zero carbon» (replacing kerosene combustion with hydrogen combustion in modified gas-turbine engines), «true zero» (transition to electric cruise motors with hydrogen fuel cells or electric batteries). The **tasks** to be solved are as follows: learning of the ways and detection of advantages and problems from the point of view of efficiency, technical complexity, economy, ecology, and implementation possibility in conditions of limited funding. The **methods** used are: search of the corresponding information sources in the Internet and their analysis on the basis of operational experience in the aviation branch. The following **results** were obtained: in terms of found information sources, data about existing greenhouse gas emissions and their predictive estimations, history of international agreement development as for greenhouse gas emission reduction were briefly stated; actuality of this problem with a view to mitigate the environmental impact was stressed; and the advantages and problems, which should be solved to implement each of the considered ways, were summarized. **Conclusions**. The scientific novelty of the results obtained is as follows: 1) information from numerous sources of literature that clarifies classification, the advantages, and the problems that should be overcome for each ways implementation, was summed up in the review article; 2) additional inherent disadvantages, which are integral to some of the ways (low efficiency, high technical complexity, schedule delays, cost overruns, funding instability, doubts in their reasonability from ecological considerations), are shown as a result of analysis and historical analogy. The direction of the following research in this field is outlined.*

Keywords: *greenhouse gas emissions; gas-turbine engine; emission reduction ways; sustainable aviation fuels; hybrid electric power plants; hydrogen aviation; fuel cells.*

Introduction

International Energy Agency (IEA) in its statistic collections (2017 and 2019 editions) [1, 2] affirms that, the share of transport within CO_2 emissions makes 24 %; and it grows by 2 % annularly in absolute figures. During 27 years (from 1990 till 2017), CO_2 emissions of world aviation increases by 126.4 % (that is by 4.7 % annularly at an average). In absolute figures CO_2 emissions of world aviation made nearly 1.8 % of anthropogenic CO_2 emissions in 2017.

Aviation Transport Action Group (ATAG) in its reports (2016 and 2020 editions) [3, 4] announce that, CO_2 emissions of world aviation makes 2.1 % of all anthropogenic CO_2 emissions.

It is assumed that, total CO_2 and NO_x emissions of world aviation from 2018 till 2050 will grow as mach as 2.6 and 3.2 times correspondingly, bat during the landing and takeoff cycle – as mach as 3.8 and 2.4 times [5]. As predicted, number of passenger flights in 2023-2042 increases from 3.6 % [5, 6] till 6.1 % [7], and cargo flights is by 3.2...3.5 % [5, 6] annularly. According to data of Airbus [6], ICAO [8], IATA [9], the share of commercial aviation in total anthropogenic CO_2 emissions from 1990 till 2019 is rather stable and makes approximately 2 %.

As early as in 1997 in Kyoto Protocol [10], a desire to reduce concentration of greenhouse gases in atmosphere to the level, would not constitute danger was stated. Developed countries undertook that, their overall emissions of greenhouse gases do not exceed the amounts, established by this Protocol (92...95 % relatively level of base year), and to reduce their overall emissions by at least 5 % below 1990 levels in the period 2008 to 2012.

In 2001, European Commission [11] set a goal to reduce CO_2 emissions by 50 % and NO_x – by 80 % till 2020. In 2011, European Commission [12] set a goal to cut CO_2 emissions by 75 % and NO_x by 90 % till 2050 as compared with 2000. In 2013, ICAO [8] set a goal to reduce CO_2 emissions by 50 % in 2050, as compared with 2005. In 2015 in Paris Agreement [13], the goal was sat to hold the increase in the global average temperature to well below 2 ºC above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 ºC above pre-industrial levels. Despite the pandemic in 2020, ICAO [9] confirmed its intensions mentioned above. In 2021, the commercial aviation established a challenging goal to achieve net-zero carbon emissions by 2050 (Fig. 1) [14, 15].

Thus, the problem of reduction of emissions of greenhouse gases (in the first place CO_2 and NO_x) is extremely actual one for the following development of commercial aviation and for mitigation of environmental impact.

1. Classification of Ways to Mitigate Harmful Emissions of Commercial Aviation

In the Roland Berger survey [16], the five possible ways to mitigate harmful emissions to the atmosphere were given: continued evolution; «net-zero»; electric hybrids; «zero carbon», and «true zero» (Table 1).

The authors denote advantages of hydrogen application in comparison with SAFs (considerable reduction of harmful emissions to the atmosphere, possibility to use solutions from other branches of industry), and in comparison with electric batteries (higher gravimetric density, relatively fast refueling capability).

But hydrogen application has also some drawbacks: necessity of engine considerable redesign, problem of hydrogen (having too low volumetric heat of combustion and high diffusion coefficient) storage onboard aircraft, unforeseen consequences of increased water emissions to the atmosphere, sustainable production of sufficient quantity of hydrogen, necessity of ground servicing infrastructure improvement, great cost.

The authors conclude that, in future small aircraft having short flight ranges will turn to electric motors with batteries; regional and narrow-body airplanes will be the battleground between hydrogen turbofans and HEPP; big and heavy aircraft turn to SAFs application.

It seems pointful to consider these ways a little bit particularly.

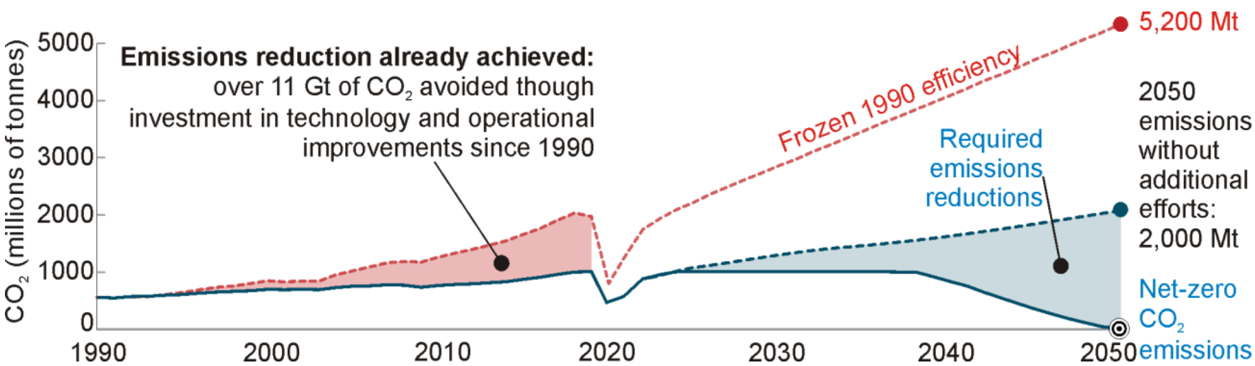

Fig. 1. Quantity of world aviation CO_2 emissions vs. years [14]

Table 1

Ways to mitigate harmful emissions to the atmosphere by commercial aviation [16]

Continued evolution	**«Net zero»**	**Electric hybrids**	**«Zero carbon»**	**«True zero»**
Methods that partially reduce greenhouse gas emissions: gas-turbine engine (GTE) efficiency increase, improvement of airplane design and structure, air traffic control system, etc.	Methods that reduce net emissions: **Offsets** – funding tree planting, renewable energy projects, etc. to mitigate CO_2 emissions; **Sustainable aviation fuels (SAFs)** – biofuels, waste-to-fuel, synthetic fuels.	Methods that reduce greenhouse gas gross emissions by 10...50 %: **Parallel** hybrid-electric power plants (HEPP); **Series** HEPP; **Series/parallel** HEPP; **Turboelectric** power plant (PP); **Partial turboelectric** PP.	Methods that reduce carbon gross emissions to zero: **Replacing kerosene combustion with hydrogen combustion in modified jet engines**.	Methods that reduce all gross emissions to zero: **Transition to electric cruise motors with hydrogen fuel cells** or **with electric batteries** (which are charged at ground from renewable sources).

2. Continued Evolution

ATAG in its reports (2016 and 2020 editions) [3, 4] states that, aircraft fuel efficiency since 2009 till 2020 has been improving by 2 % annularly due to aerodynamics refining, application of new technologies, composite materials (for aircraft main load-carrying structure, seats, cabin trolleys, Kevlar cargo containers (which also ensure fire-resistance) [17]) and composites with ceramic-matrix (in engines); application of additive technologies (which reduces both part mass and manufacturing waster) [18]; winglets installation (which can reduce fuel consumption by around 4 %); using tablet computers by flight crew instead of paper-based flight manuals (which can weight up to 20 kg) [4].

Transition from stepped climb and descend to continuous ones with the goal to reduce fuel consumption (which gives on average reduction of CO_2 emissions by 50 kg and 150 kg per flight accordingly) [19]. More close informational interaction between airlines and airports allows reducing in-flight waiting time [4]. Now, many airlines use only one engine during taxing, but it is planned to apply towing with electric cars [17] or electric motors built-in airplane landing gear wheels [18]. Using ground sources of electric power and high-pressure air for environment control system and engine starting instead of auxiliary power plant (APU), allows avoiding additional fuel consumption for the APU [4]. Engine ingestion of dust, insects and other foreign matter during taxing, takeoff and landing results in fuel consumption increase, thus regular internal engine washing allows to avoid this (each extra kilogram of burned fuel gives 3.15 kg of CO_2) [20].

Transition from traditional for mid-20th-century zigzagging flight trajectory to optimized (close to orthodromy) and more precise trajectory due to application of satellite navigation technologies and procedures referred as «performance-based navigation» [4]. Substitution of the traditional flight trajectory along fixed routes by ground-based navigation aids avoiding reserved areas off airspace to more optimal trajectory, taking into account weather conditions, especially wind direction, due to application of «free route airspace» technology and satellite navigation, decreasing sizes or temporal free up these reserved areas (but here questions of aircraft nose influence to ground people appear) [18, 21]. Such projects as Single European Sky ATM Research (SESAR) in Europe [22] and Next Generation Air Transportation System (NextGen) in USA [23, 24] are started with the purpose to optimize routes, which promise considerable reduction of greenhouse gas emissions.

Reduction of CO_2 emissions is also achieved by airport means: application of LED lighting, electric ground transport and equipment using renewable sources of electric energy, and also due to transition from airport waster utilization in waster tip to its recycling and energy production from the waster (using materials, which allows easy recycling) [4, 25]. Decrease in quantity of airport waster due to single-use means (utensil, bottles, cutlery) substitution with reusable ones, which is banned now according to hygiene considerations [4]. Now, rules are developed [26, 27] to resolve this contradiction. Work is also underway for ecological utilization of retired airplanes [28].

Looking for new configurations of commercial airplanes continues. M.-S. Liou et al. in NASA report [29] analyze different versions of engine arrangement in airplane of blended wing-body (BWB) configuration (two turbofans in separate nacelles with pylons above the body, three blocks of a turbofan with mechanical drive for two additional fans on each side of each nacelle, 16 electric motors in common nacelle above the body without pylons). Due to closed integration and optimization of engine arrangement in airplanes of these configurations, authors hope to get considerable reduction of fuel consumption (by 33...60 %) and NO_x emissions (by 55...80 %) in comparison with the best airplanes of 2005.

W. Graham et al. in publication [30] consider several configurations of commercial airplanes (tube-and-wing (TW), BWB, laminar flying wing (LFW)) and their possibilities to reduce harmful emissions to the atmosphere. As far as these possibilities are insufficient to achieve goals set by European Commission [12], the authors make conclusion, that big investments are required in scientific research and technology development.

F. Linke et al. consider possibility of Intermediate Stop Operations (ISO) for commercial flights, which allows reduction of gross CO_2, NO_x, H_2O, and SO_2 emissions due to decreasing of fuel storage [31].

One more known (but almost forgotten in aviation) technology for GTE characteristic improvement is coolant injection in its compressor or combustor. Earlier, it was used for short-term thrust increasing during takeoff, but it was canceled when enough powerful engines appeared. Now, this technology is again considered as one of the ways to decrease NO_x emissions [32, 33].

Thus, advantages of continued evolution are those, that it is performed by clear improvement methods of aircraft, engines and infrastructure, some of which have already been implementing, in addition this way distinguishes by minimal technical risk and required investments (which becomes critical taking into account world economical crisis). The drawback of continuous evolution is that, it only allows reduction in quantity of CO_2 and NO_x emissions, which is assumed insufficient, accounting pace of world industry development.

3. «Net Zero»

This way is based on two methods: offsets and sustainable aviation fuels (SAFs) [16].

Offsets mean increase in taxes and introduction of fines for airports and airlines in case when their greenhouse gas emissions exceed limits (which leads to cost of flight increase for passengers). Collected many should be directed to funding tree planting, renewable energy projects, etc. to mitigate CO_2 emissions [16]. But practically, these many are not always reinvested in environmental improvement measures; which causes criticism of this method by airlines [4].

SAFs (which are also referred as biofuels, renewable aviation fuels, renewable jet fuels, alternative fuels, and biojets) are safe replacements for conventional (fossil-based) fuel that could reduce carbon emissions. They are almost chemically identical to traditional jet fuel, but they are generated from feedstocks, that absorb CO_2 and provide a net (that is during all fuel lifecycle) reduction in CO_2 emissions when compared to fossil fuels [34].

T. Edwards et al. in publication [35] stress that, alternative aircraft fuels derived from coal, biomass, tar sands, and oil shale are desirable in terms of reducing dependence on petroleum for both military and commercial aviation; in addition this fuels should be fully interchangeable with current fuels in performance and handling («drop-in»), with no degradation of safety-of-flight, cost-competitive, sustainable, capable of being produced in significant quantities, and have low lifecycle greenhouse gas footprint.

SAFs include the following: traditional aviation fuels (but produces from sustainable feedstocks: waste oils and fats, municipal solid waster, forestry residue, industrial waste gases, CO_2 from the atmosphere etc. and using low-carbon electricity), biofuels (produced from plants, algae, vegetable oil, animal fat, sugar cane etc.), low-carbon fuels; liquid natural gas etc. [16, 4, 36, 17].

It's assumed that, plants for SAF production should grow on land that qualified as marginal, abandoned or unviable for growing food, but is suitable for growing energy crops. So SAF production can give economic benefits to developing countries, where the plants will grow. But production of biofuels can lead to negative changes in the use of agricultural land and water, increase in food prices, influence on local environments via irrigation, pesticides and fertilisers [34].

As of January 2022, seven SAF production processes have been approved by ASTM International. SAF are allowed to add into fossil fuels in concentrations, which do not exceed 50 %. It is planned to achieve 100 % concentration till 2030. Emissions from the combustion of SAF are comparable to fossil fuels; than the reductions in greenhouse gas emissions originate during their production [37].

Fuels produced by Fisher-Tropsch process generally produces approximately 2.4 % less CO_2, 50…90 % less particulate matter, and 100 % less sulfur than conventional petroleum-based fuels; these fuels also have excellent low temperature properties and superior thermal stability that can improve high altitude operation and low temperature starting [38]. But total life-cycle carbon emissions of these fuels can be twice those of conventional fuels (without involving any carbon capture and sequestration technology during fuel production) [39].

Biofuels derived from camelina, micro-algae, and jatropha deliver 70 %, 58 %, and 64 % of life cycle emissions savings, respectively, relative to Jet A-1; but biofuels have some drawbacks that include low energy density, poor high-temperature thermal stability, storage instability, etc. [40].

SAF are primarily composed of iso- and normal alkanes with a small fraction of cyclo-alkanes, negligible aromatics and almost no heteroatom and sulfur compounds, which results in high flashpoint (43…55 ºC), low freeze point (-49…-78 ºC) and high thermal stability. But from other hand side it worsens fuel lubrication properties and leads to potential failure of engine seals (because aromatics cause seal to swell and prevent leakage) [38].

A. Goldmann et al. in publication [41] consider five potential electrofuels (n-octane, methanol, methane, hydrogen, and ammonia), that is fuels, which are neutral with respect to greenhouse gas emission, and use renewable energy for their synthesis. Authors stress, that the main problem of aviation transition to renewable electric energy utilization for thrust generation is limited energy storage in onboard batteries. An alternative is renewable electric energy transformation on the ground in gaseous or liquid fuel (electrofuel), its uplifting and further utilization onboard aircraft as an energy source. Basing on digital simulation of chemical combustion processes and turbine operation, the authors give preference to n-octane, emphasizing necessity of engine combustor considerable redesign in case of transition to other electrofuel utilization (methanol, methane, hydrogen and ammonia).

H. Braun in publication [42] states that, even if all of the corn in the USA was used to produce biofuel (ethanol), it would only displace 12 % of the gasoline now used, but even the relatively small amounts of biofuels being produced in 2008 leaded to substantial increase of food prices worldwide. Moreover, such biofuels as ethanol is not renewable because it depletes the soil 18 times faster than it can recover, and it typically requires more energy from fossil fuels to make them from corn than the ethanol will generate when it is used as a fuel.

In 2020, utilization of SAF made about 1 % of total quantity of aviation fuel. Advantages of SAFs are: possibility of their production from sustainable feedstocks and considerable reduction of CO_2 emissions during this production. The drawbacks of SAF utilization are: cost higher than of traditional ones and limited production quantities [3, 4].

As the majority of emissions come from flights of large aircraft, where both electric and hydrogen would not be viable until well into the middle of the century; SAF remain the most important energy shift for aviation in the medium and potentially long-term [34].

It is assumed that, SAF will contribute between 53 and 71 % of the emission reductions needed to get to net-zero by 2050. But for this purpose, it is necessary to provide an adequate supply of sustainable feedstock, low-carbon energy sources and production capacity [34].

Reminding high school chemistry course, it is easy to estimate carbon mass fraction in alkanes (C_nH_{2n+2}), alkenes or cyclo-alkanes (C_nH_{2n}), alkynes (C_nH_{2n-2}) and monobasic alcohols ($C_nH_{2n+1}OH$) (Fig. 2):

$$\omega(C)=\frac{12n}{12n+2n+2}; \qquad \omega(C)=\frac{12n}{12n+2n};$$

$$\omega(C)=\frac{12n}{12n+2n-2}; \quad \omega(C)=\frac{12n}{12n+2n+2+16}.$$

where n is the of number carbon atoms in molecule.

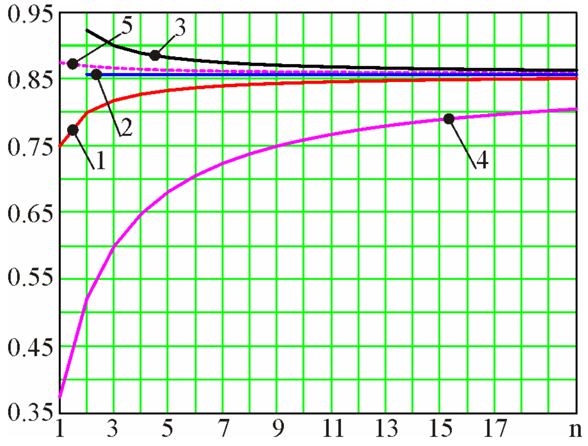

Fig. 2. Carbon mass fraction in molecules of: 1 – Alkanes; 2 – Alkenes or cyclo-alkanes; 3 – Alkynes; 4 – Monobasic alcohols; 5 – Together with oxygen in monobasic alcohols

It is clear from the graphs, that methanol has the lowest carbon mass fraction (0.375) among considered substances, which is 2.246 times lower than for octane (0.842).

Writing down oxidation equations for these substances:

$$\begin{array}{ll} 2C_nH_{2n+2}+(3n+1)O_2 & =2nCO_2+2(n+1)H_2O; \\ 28n+4 & 88n \\ 1 & x \end{array}$$

$$\begin{array}{ll} 2C_nH_{2n}+3nO_2 & =2nCO_2+2nH_2O; \\ 28n & 88n \\ 1 & x \end{array}$$

$$\begin{array}{ll} 2C_nH_{2n-2}+(3n-1)O_2 & =2nCO_2+2(n-1)H_2O; \\ 28n-4 & 88n \\ 1 & x \end{array}$$

$$\begin{array}{ll} 2C_nH_{2n+1}OH+3nO_2 & =2nCO_2+2(n+1)H_2O; \\ 28n+36 & 88n \\ 1 & x \end{array}$$

we get, that complete combustion of 1 kg of alkane produces $x=88n/(28n+4)$ kg of CO_2; 1 kg of alkene (or cyclo-alkane) – $x=88n/28n=3.143$ kg of CO_2; 1 kg of alkyne – $x=88n/(28n-4)$ kg of CO_2; 1 kg of monobasic alcohol – $x=88n/(28n+36)$ kg of CO_2 (Fig. 3).

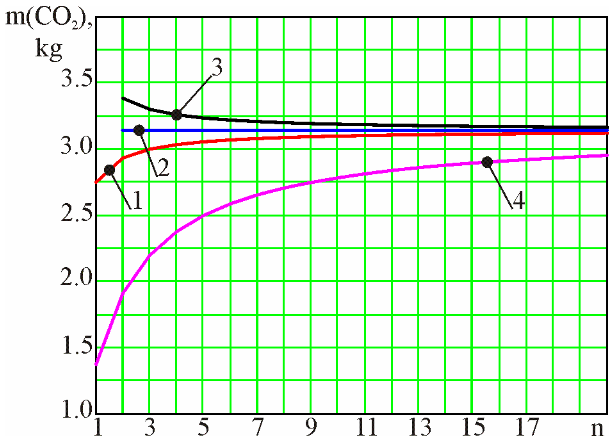

Fig. 3. Mass of CO_2 produced during complete combustion of 1 kg of: 1 – Alkanes; 2 – Alkenes or cyclo-alkanes; 3 – Alkynes; 4 – Monobasic alcohols

That is complete combustion of 1 kg of methanol produces 1.375 kg of CO_2, which is 2.246 times lower than complete combustion of 1 kg of octane (3.088 kg) does. Taking into account the fact, that due to hydrogen bonds, methanol is a liquid under normal temperature and pressure, its transportation, storage and uplifting are rather easy compared with ammonia or natural gas, letting hydrogen alone.

Thus, advantages of «net zero» way are usage of traditional structures of aircraft, engines, and infrastructure, little technical risk and required investments (in aviation branch). This way is also being partially implemented. The drawback of the «net zero» way is that, it allows only reduction in quantity of net CO_2 emissions, but these emissions during GTE operation at cruising altitude remains as is, and also big required investments in these fuel manufacturing.

4. Hybrid-Electric Power Plants

HEPP represent a bridging technology towards all-electric PP and allow manufacturers to obtain operational experience with systems, consisting of two different energy sources, driving propulsors, until batteries reach required technological level [43].

A. Isikveren et al. in publication [44] have done wide conceptual research of HEPP parameters using gradient method. Authors use a term Degree-of-Hybridization (DoH) of power and for energy for HEPP classification:

$$H_P = \frac{P_e}{P_\Sigma}, \qquad H_E = \frac{E_e}{E_\Sigma},$$

where P_e, P_Σ are power of the second power source (electric motors) and total power of HEPP; E_e, E_Σ are energy of the second source (battery) and total energy on board A/C.

According to the Committee on Propulsion and Energy Systems [45], airplane's electric PP can be classified in six different schemes (Fig. 4, Table 2).

Table 2

Classification of PP [45]

Power plant	H_P	H_E
All electric PP	1	1
Series HEPP	1	(0...1)
Parallel HEPP	(0...1)	(0...1)
Turboelectric PP	1	0
Series/parallel HEPP	(0...1)	(0...1)
Partial turboelectric PP	(0...1)	0
Traditional PP	0	0

The first is all-electric PP (Fig. 4, a), which use batteries as the only source of energy and are limited by the power-to-weight ratio of batteries. PPs, where batteries provide extra power for propulsion are called HEPP. In series HEPP (Fig. 4, b), only electric motors are mechanically connected to the propellers/fans. Turboshaft engine drives a generator that provides electric power for the electric motors. Extra power (e. g. at take-off) can be provided by the batteries. In a parallel HEPP (Fig. 4, c), the GTE and electric motors with propellers/fans can produce propulsion in parallel, and electric motors can be powered by batteries, the GTE or both. Series/parallel HEPP (Fig. 4, e) has one or more propellers/fans that can be driven directly by a GTE as well as other propellers/fans that are driven by electrical motors. The motors can be powered by a battery or by a GTE-driven generator. Turboelectric PP (Fig. 4, d) uses a turboshaft engine with an electric generator as only source of electric energy for electric motors rotating propellers/fans. Partial turboelectric PP (Fig. 4, f) distinguishes from series/parallel HEPP by electric battery absents only.

HEPP promise set of advantages.

1. Depending on electric power source, reduction of CO_2 in-flight emissions [46, 47].

2. More efficient energy conservation and transformation, more-reliable systems [48]. Even if electric energy is produced by ground gas turbines, their efficiency is usually higher than of aviation GTE. In case of superconductive electric components application, electric efficiency is close to unit [46].

3. Lower noise [48, 47].

4. As GTE power settings can be constant during the entire flight, it minimizes mechanical and thermal stresses due to load variations. As a result, component service life increases, that allows to extended maintenance intervals [43]. M. Schneider et al. in publication [49] stress that, if extreme turbine inlet temperature levels during takeoff and climb can be avoided as the power surplus can be provided by the battery, then thermo-mechanical fatigue and low cycle fatigue for the first turbine stages and combustor parts can be significantly reduced. Thus, engine aging effects are reduced and maintenance intervals extended, which saves financial and environmental recourses.

5. The constant power setting also offers opportunity to optimize efficiency especially around corresponding base load point [43] (but according to calculation of M. Holsteijn et al., this improvement makes about 1.0 % [50]). Thus not only fuel resources, but also material resources and energy for part production are saved [43]. Multiple studies have shown that HEPP can reduce the fuel burn in regional flights by around 7…10 % with the envisaged 2030-2035 technology in comparison to conventional propulsion system [50]. But PP dedicated for fully electric taxiing system could provide similar (7 %) savings of fuel burn on an A-320 class aircraft, at less effort and costs [50].

6. As turbine and fan (of turboelectric and series HEPP) are not interconnected mechanically, then each of the units can rotate with optimal angular speed, thus operate at optimum mode (as geared turbofans) [46]. But in parallel HEPP, electric motor connected to low pressure turbine shaft can cause compressor surge and push the compressors away from their most efficient operating points, to avoid that one more electric motor can be connected to high pressure turbine shaft, but this increases mass and complexity of HEPP. One more problem is arrangement of the electric motors [50].

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

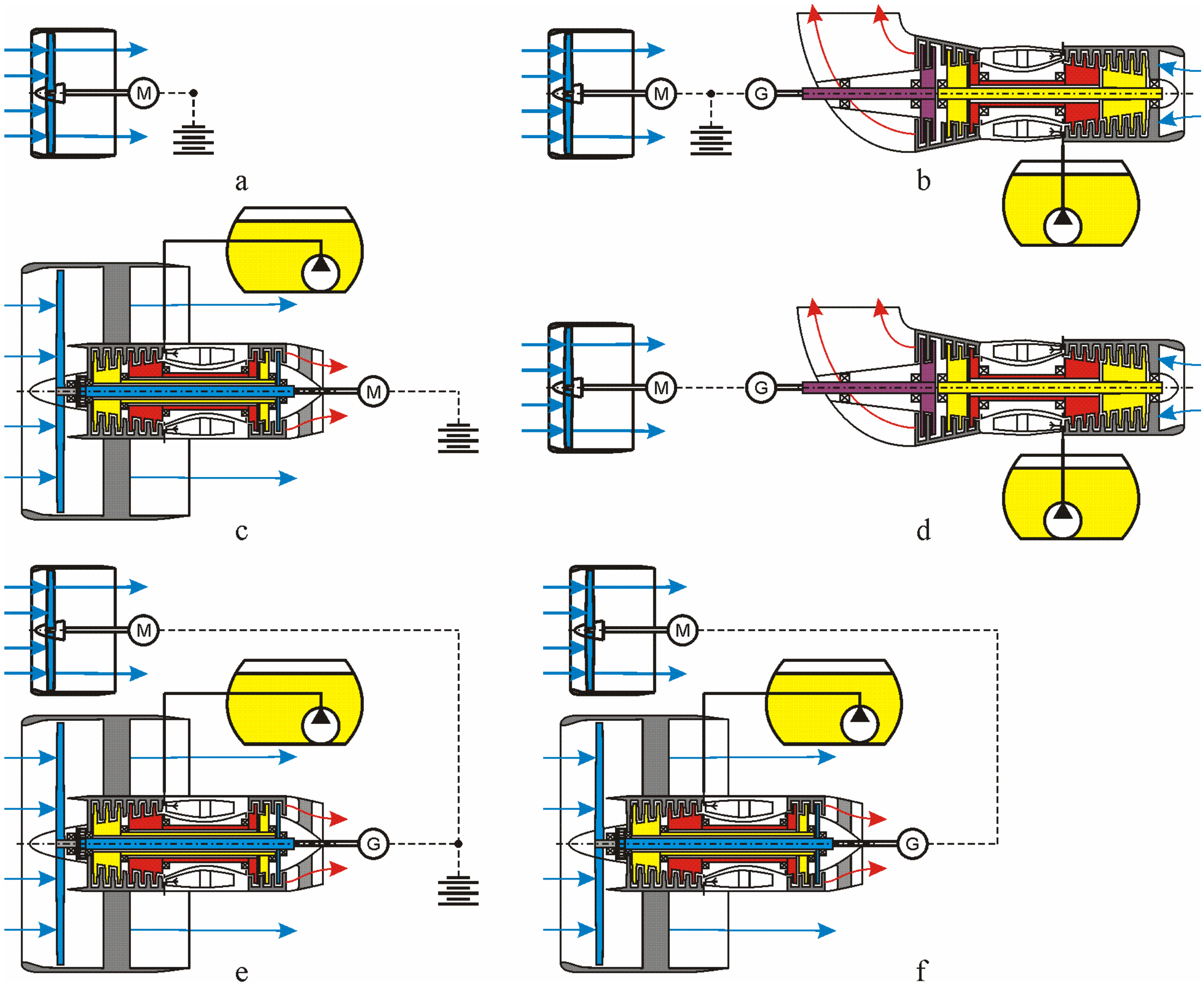

Fig. 4. Airplane's electric PP schemes [45]: a – All electric PP; b – Series HEPP; c – Parallel HEPP; d – Turboelectric; e – Series/parallel HEPP; f – Partial turboelectric

7. There is a possibility to rotate some fans by a turbine via reduction gearboxes (thus having very high bypass ratio). It allows increasing of propulsive efficiency of PP by 4...8 % [46], but it makes PP more complicated and decreases its reliability.

8. HEPP allows the efficient application of wing tip vortices without having the efficiency and weight penalties of small GTE, the case of four or six engines installed lead to less oversizing of each propulsor [48]. Electric motors with propellers arrangement in wing tips allow reduction of the tip vortexes, which gives opportunity to decrease aerodynamic drag by 5... 10 % [51], and improvement of lift properties of the aircraft with limited weight and cost increases [48].

9. It is assumed that, application of boundary layer suction reduces aerodynamic drag coefficient (or increases PP propulsive efficiency). Utilization of multiple electric motors allows boundary layer suction from greater area, thus efficiency of low-power electric motors keeps rather high (as opposite to efficiency of gas-turbine or reciprocating engines) [46].

10. It is assumed that, application of distributed propulsion allows: aerodynamic drag decreasing, lift force coefficient increasing, and air twist decreasing [46]. The new arrangement of propulsors can lead to better aerodynamic lift properties of the wing [52]. Depending on purpose and configuration of an airplane, aerodynamic drag can be decreased by 0...8 % [53]. Lift force coefficient increase (up to 2.4 [54, 55, 51]) allows reduction in wing area and friction drag, and also increasing in lift-to-drag ratio up to 20 [56].

11. Decrease in propeller diameters of distributed propulsion reduces speed at their tips, which allows their mass decreasing and simplifies meeting of bird strike requirements. But from other hand side, boundary layer suction by propellers forces make them stable to disturbances, that increases their mass. In addition, distributed propulsion compels to reinforce bigger part of

airplane airframe for the case of propeller blade destruction [46].

12. Increase in number of engines (distributed propulsion application) can lead to lower oversizing factors of the power rating for each propulsor which is sized in modern airplanes from condition of continued takeoff with specified altitude gradient in case of one engine inoperative. The vertical tail size is also designed for steering momentums in the case of one engine inoperative. When the engines are controlled and differential thrust is used, smaller momentums have to be handled by vertical tail, thus its sizes can be decreased [57], so all these increases HEPP efficiency [46].

13. If electric energy is cheaper than kerosene (in terms of specific energy), it can decrease operation expenses. It is assumed that, application of electric motors and batteries can reduce airplane maintenance expenses, but it is not a fact yet [46].

But HEPP application requires solving a lot of problems.

1. Two the most important parameters of electric PP are: specific energy (energy ratio to mass unit of energy storage device, Wh/kg) and specific power (device power ratio to its mass, MW/kg or MJ/kg). Thence it is easy to see the first technological problem (the main problem of electric batteries): their specific energy (200 Wh/kg) is practically 50 times lower than kerosene specific energy (11900 Wh/kg). It leads to considerable increase in total energy consumption and takeoff mass [46] (approximately by 5.5 % basing on 2030-year expected technology [50]), decreases payload and flight range [43].

2. In spite of rather high efficiency of electric components, necessity of their cooling is a technological problem [46]. Increase in number of «hot points» of the aircraft, where heat is produced, and also increase in total amounts of heat generated, necessity of effective regulation of various thermal loads, which are generated by HEPP electrical components, turn designing of the thermal management system, for an airplane with HEPP, into a very complicated task, due to its impact on the cooling drag, aircraft's total mass and overall performance [47].

O. Mylonas, et al. in publication [47] investigate the possible operating media of a selected thermal management system, and their impact during the conceptual design phase of the system. It is possible to have an air cooled system, but its performance is highly dependent on the flight altitude. Opting for a liquid cooled architecture, leads from the one hand to a more robust system which is not directly affected by the atmospheric conditions. It requires a lower coolant mass flow, but on the other hand it increases overall system complexity and mass.

3. A problem of electric batteries is absence of mass decrease during flight, which causes additional aerodynamic drag and actually limits flight range. Mass ratio of electric PP can reach 33 % (comparing with 10.5 % for B-737/777) [46].

4. Although electric batteries application allows to get rig of fire and explosion hazard problems of liquid fuel, but it raises a new safety problem: thermal runaway, when self-sustaining increase in temperature and pressure in battery occur, which can mead to fire and toxic gases release. Thermal runaway can result from overdischarging, overcharging, and short-circuits. It is necessary to take into account hazards of high-voltage equipment and superconductivity loss [46].

5. One more problem is absence of reliable models for estimation of aerodynamic performance of novel aircraft configurations, especially with distributed propulsion, and also cost price of electric and hybrid aircraft [46].

A lot of authors investigated HEPP application to modify airplanes of various classes (Do 226 [49], ATR-42-500 [48, 58], Fokker 100 [59], Airbus 320 [60]) or engines (turbofans [61], turboprops [62]), but all of them stress that, imperfection of existing technologies considerably decreases payload [49], or increases takeoff mass [58], or an airplane could not provide required reserve mission scenario [58], or even emits 12 % more CO_2 than conventional airplane (accounting for the battery emissions due to recharging) [58], or onboard battery recharging capability is limited (due to a lower system efficiency associated with two-stage conversion process i. e. first, from chemical energy into mechanical form and further from mechanical to electrical form) [60], and extra fuel consumption [48]. In addition, the improvement potential in specific fuel consumption from parallel hybridization is low [62], but HEPP requires a trade-off between the characteristics of the GTE and the electric power sub-systems [61].

A. Isikveren et al. in publication [44] present analytical expressions that parametrically describe any advanced HEPP, and use them to find optimal parameters of HEPP ($H_P = 0.30 \ldots 0.65$ and $H_E = 0.10 \ldots 0.12$) from the condition of energy specific air range maximization.

R. Ghelani et al. believe that, a high hybridization by power and low hybridization by energy is the most suitable combination for fuel burn and energy consumption reduction; these together with ranges below 1292 km are the only cases where the redesigned aircraft with HEPP can have benefits in fuel burn and energy consumption relative to the baseline aircraft [59].

B. Brelje et al. in publication [46] stress that, hybrid and electric airplanes now can have advantages at low flight ranges. M. Holsteijn et al. in publication [50] concluded that, even at the optimistic technology levels assumed, parallel hybrid-electric propulsion is not likely

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

to be used in the next-generation short to medium range aircraft. For long-range airplanes, the additional mass of the electric PP makes it difficult to achieve any substantial fuel saving.

According to optimistic estimations, it is assumed that, the parallel scheme of HEPP can be implemented first (not before 2030-35 timeframe) (as other HEPP schemes need MW-class superconducting generators and transmission systems, and newer airframes) [59], turboelectric PP can appear within the next 30 years [63], but cryogenic electrical components will be ready for installation in aircraft before 2050 [46].

Other authors believe that, despite the fuel savings and benefits of electric taxiing with a HEPP, commercial aircraft with parallel HEPP are not expected to be introduced in the coming two decades. HEPP will require a significant redesign of the aircraft PP, while the majority of the fuel savings can be achieved by incorporating an electric taxiing system, as a ground-based electric taxi system will require less effort to be developed than a HEPP [50].

5. «Zero carbon»

As far back as 1954, investigation of hydrogen application as aviation fuel for high-altitude (H=20...24 km) military airplanes did start in USA (because hydrogen burns good under low pressure, mass of hydrogen turbojet should be a half of mass of kerosene turbojet). It is clear from Fig. 5 that, liquid hydrogen was planned to arrange in cylindrical fuel tanks inside fuselage 1, wings 2 and under wings 3 [64, 65].

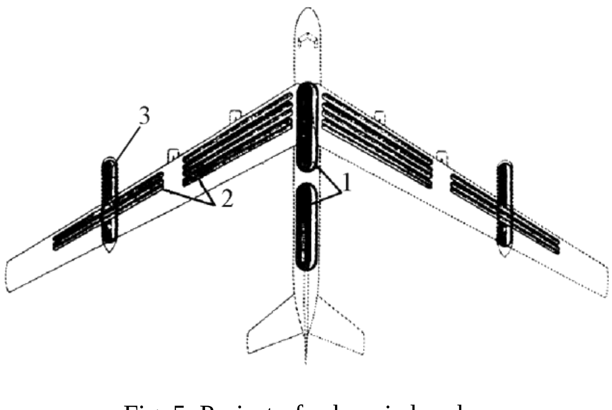

Fig. 5. Project of subsonic bomber using hydrogen fuel [65]

One of the first propositions of passenger airplane using liquid hydrogen was stated by G. Brewer et al. in NASA report [66] as early as 1976. The authors estimated that, aerodynamic drag of hydrogen airplane having external fuel tanks (EFT) increases by 15.8 %, but one having internal tanks is by 4.1 % comparing with kerosene airplane; and they concluded that, mass and aerodynamic parameters of airplane having EFT becomes worse with flight range increase, and even short-range airplane having EFT is not competitive [66].

Liquid hydrogen was used as fuel in some experimental airplanes. In 1956–1959, within project «Bee», left EFT of Martin B-57B bomber was reequipped for liquid hydrogen storage, which next preheated with external air flow in heat-exchanger, and in gaseous state entered left engine J-65, in which a collector with nozzles for hydrogen was added (Fig. 6). Tests shown the turbojet capability to operate with hydrogen up to altitudes of 27.4 km (3...7 km higher than with JP-4), and specific fuel consumption was by 60...70 % lower than for JP-4 [64].

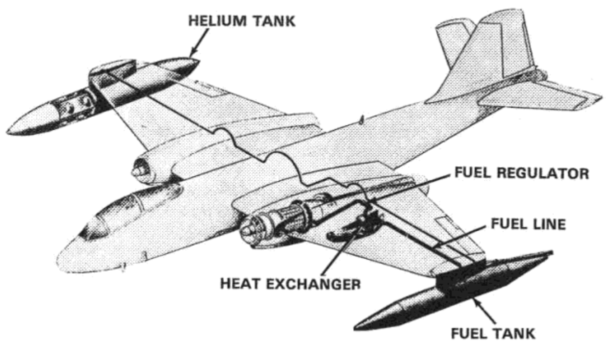

Fig. 6. Martin B-57B experimental airplane (project «Bee») [64]

Later, project of cargo airplane Lockheed L-1011 using liquid hydrogen was developed (Fig. 7) [42]. In 1988, right NK-8-2 engine of Tu-154 passenger airplane was replaced with NK-88 engine using liquid hydrogen; this airplane was tested under the name Tu-155 (Fig. 8), and tardy was converted to natural gas [67].

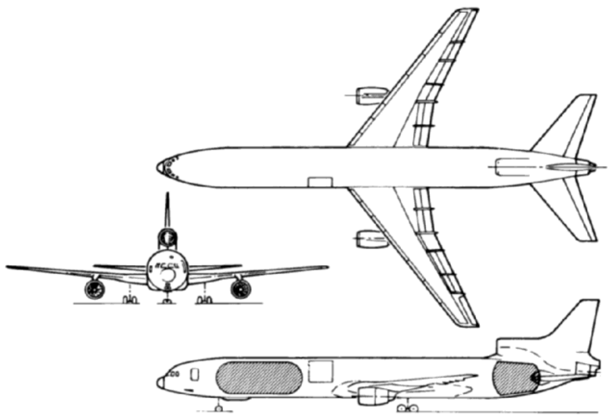

Fig. 7. Project of L-1011 cargo airplane modification to use hydrogen fuel [42]

From the beginning of XXI century, aviation industry returns to the idea of hydrogen application for commercial aircraft for ecologic reasons. From 2000, European Commission funds project Cryoplane – the first full-scale project of hydrogen airplane [68]. In 2022, Airbus reports [69] about plans to develop an airplane with two hybrid turbofans (200 pas., flight range – 3706 km) and an airplane with two hybrid turboprops (100 pas., range – 1853 km) where liquid hydrogen is stored behind rear pressurized frame, an airplane of «blended wing body» configuration with two hybrid turbofans (200 pas., range – 3706 km) where liquid hydrogen is stored under wing.

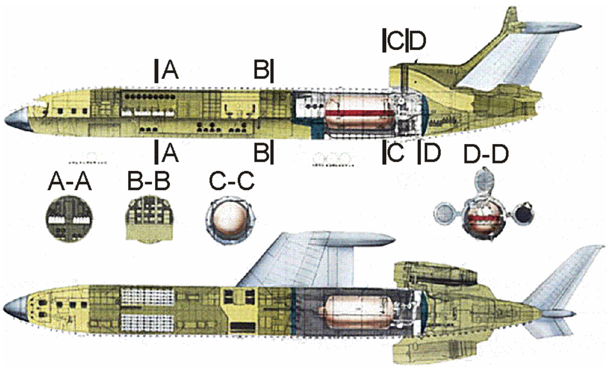

Fig. 8. Tu-155 experimental airplane using hydrogen fuel [67]

Hydrogen application in gas-turbine engines gives the following advantages:

1. In case of hydrogen production from sustainable sources (water electrolysis), complete absence of CO_2 and CO emissions (within the whole fuel life-cycle) [16].

2. High hydrogen's heat of combustion (Table 3) from one hand side leads to the fact that mass of hydrogen fuel should be 2.78 times lower comparing with mass of kerosene, which can decrease takeoff mass and required wing sizes. But from other hand side, lower decrease in fuel mass requires bigger thrust both at cruise mode, and during approach to landing, and also lower increase in cruising flight altitude (that worsen fuel efficiency). Which of these trends will prevail is now a subject of scientific discussion [70, 71, 72].

3. Possibility to decrease NO_x emissions (due to lower mixture residence time inside combustor, because hydrogen has higher flame speed) [73].

4. Liquid hydrogen utilization as heat sink allows to cool down air in compressor (thus decreasing fuel consumption) [74].

5. Leaks of hydrogen (liquid or gaseous) are quickly evaporated and dissipate in the atmosphere, reducing the fire hazard [75]. It is assumed that, hydrogen fire should quickly dissipate and do less damage than a similar gasoline fire [73].

But rather complicated problems should be solved for hydrogen application:

1. Low hydrogen's volumetric heat of combustion, which leads to considerable increase in required volume of fuel tanks [65].

2. Low tank gravimetric efficiency (mass of fuel inside this tank ratio to this fuel mass together with the tank mass) [73].

As it is known, hydrogen can be stored in compressed or liquid state. Hydrogen storage in compressed state gives opportunity of it long-term storing and simplifies transportation and refueling systems [73]. Challenges of compressed hydrogen tanks are as follows: hydrogen embrittlement of tank material (which dramatically decreases the material yield stress, especially under negative temperatures, that increases the required safety factor and the tank mass) [76] and hydrogen permeation [77] (for launch vehicle tanks, 0.25 % of hydrogen is lost [78], that makes medium around the tanks explosive one).

Hydrogen storage in liquid state offers higher volumetric heat of combustion, 2...3 times bigger density, storage possibility under low pressure (0.1...0.3 MPa), thus considerably higher gravimetric efficiency [73]. Problems of these tanks are as follows: extremely low storage temperature (under which tank materials should maintain strength, accounting cyclic temperature variation), necessity to choose tank shape having low surface area-to-volume ratio, hydrogen losses due to heating to maintain tank strength (especially before takeoff in hot day) (according to various estimations: about 0.1 % of hydrogen mass per hour [77] or about 2 % per flight [79]). Insulation is a separate problem.

Table 3

Fuel properties [73]

Property	Jet A-1	LH_2	GH_2 (35 MPa)	GH_2 (70 MPa)
Heat of combustion, MJ/kg	43.2	120	120	120
Relative heat of combustion	1	2.78	2.78	2.78
Volumetric heat of combustion, MJ/L	34.9	8.5	2.9	4.8
Relative volumetric heat of combustion	1	0.24	0.08	0.14
Storage temperature, ºC	ambient	–253	ambient	ambient
Storage pressure, MPa	ambient	0.1…0.3	35	70
Tank gravimetric efficiency, %	100	30...90	1...15 (6...9)	1...15 (5...7)

Foam, which is used in carrier rockets, can give high gravimetric efficiency, but it is cracked or delaminated under repeated thermal cycles [80], which requires its regular maintenance [76]. Multi-layer vacuum insulation (having multiple layers of foil, which reflect thermal radiation) lowers the heat leaks by two orders [77], but its gravimetric efficiency does not exceed 60 % due to required strength [81], employing composites creates problems of permeation and splitting due to different variation of properties of fibers and matrix under the cryogenic temperatures [73].

3. Tank shape selection. In case of hydrogen storage in liquid state, to minimize hydrogen heating (but in case of its storage in compressed state – to minimize tank mass) tank surface area-to-volume ratio should be low, that is hydrogen tanks should be of spherical or cylindrical shape (having length-to-diameter ratio near three), which practically excludes their arrangement inside wings, but forces to place them in fuselage or pods. Firstly, this increase the aircraft wetted area (and in case of pods – also mid-section area), thus aerodynamic drag; secondly, it does not allow wing load alleviation by fuel, but vice versa increases loads to wings, thus increasing mass of empty airplane [70, 75].

4. Arrangement of hydrogen tanks (of sufficient volume). For conventional aerodynamic configuration, they usually consider three versions of hydrogen tanks arrangement in fuselage: 1) behind passenger compartment, 2) in front and behind passenger compartment, 3) above passenger compartment. The first version suits only for short flight ranges due to considerable center-of-gravity variation [71]. The second version allows maintaining required center-of-gravity easily for medium and long-range airplanes, but excludes pilot access to the passenger compartment (thus it requires separate toilet and galley for them [66]) or results in considerable mass expenses to perform this passage [71]. The third version offers hither safety during landing (especially with landing gear up), but leads to aerodynamic drag increase about 10 % [82]. For «blended wing body» configuration, hydrogen tanks can be located on each side of the passenger compartment (where wing structural height does not allow convenient arrangement of passengers or cargo) or in the wing central section between two passenger compartments [73].

5. GTE conversion to hydrogen requires modification of their combustors owning to different stochiometric coefficient (14.7 – for kerosene; 34 – for hydrogen) and other limits of air excess coefficient for steady combustion (shifted to the lean mix, which allows turbine inlet temperature decreasing) [73].

6. As hydrogen is transported from tanks to engines in liquid state, pipelines and other elements of liquid hydrogen fuel system should be heat-insulated (placed within vacuum jacket or coated with foam) [75].

7. Separate problem is pumps for liquid hydrogen, which can continuously operate for hours and have a service life of tens of thousands of hours [73].

8. Change of material properties in contact with hydrogen and its handling procedures make a challenge [83].

9. Explosion safety. Because hydrogen has a wide flammability range and is prone to leaking, aircraft fuel system must be equipped with leak detectors [73].

10. During hydrogen transportation on the ground, problem of its leaking (but in case of its transportation in liquid state – evaporation losses) appears. These leaks are estimated within the range 1...10 % [84]. Although hydrogen is not a greenhouse gas; its presence in the atmosphere affects the other greenhouse gases, increases the lifetime of methane, the amount of water vapor in the upper atmosphere, and the concentration of ozone in the troposphere. Research quantifying the effects of direct hydrogen emission to the atmosphere is limited, which remain uncertainties [73]. Hydrogen transportation via ammonia allows using existing transportation equipment [85], but requires considerable energy losses for chemical conversions [86] and constitutes potential ecological hazards.

11. As it is known, according to production method, hydrogen can be [73]: green (produced by electrolysis from renewable energy), pink (produced by electrolysis from nuclear energy), blue (produced by steam methane reforming with carbon capturing), gray (produced by steam methane reforming), and brown (produced by coal gasification). Nearly 80 % of hydrogen produced in 2020 is gray or brown, and using of these hydrogen is not an effective way of reducing climate impact, but may be more damaging, than kerosene utilization. It is estimated that, blue hydrogen causes 9...85 % lower quantity of CO_2 emissions relatively to gray hydrogen; but during production of blue hydrogen, there are possible methane emissions, which is one of potent greenhouse gas [87, 88, 89].

12. Aircraft-Induced Cloudiness (AIC) is capable to reflect solar radiation during the day (cooling the Earth) and prevent thermal irradiation from the Earth at night (causing its warming). Scientists begin understanding impact of contrail cirrus to greenhouse effect, and also their greater quantity in locations with high air traffic relatively not long ago, and thus a lot of uncertainty remains (thin cirrus clouds and airplane contrails cannot be detected nether from the ground, no from satellites, thus it is impossible to estimate their impact in climate change). As it is known, hydrogen combustion produces 2.6 times more water vapor emissions, than hydrocarbons combustion per unit of energy, but contrails and AIC are the greatest unknown and potentially the most significant contributor to the climate impact of hydrogen aircraft. Contrails of hydrogen GTE can form

under the temperature by 10 K higher than for kerosene GTE, so in wider range of altitudes [73]. Although short-term direct climate effect of water vapor emissions is very small at subsonic cruise flight altitudes in the troposphere; but, water vapor emissions from an increasing number of flights above the tropopause, such as supersonic airplanes and certain subsonic business jets, can have a warming effect as they fly in the drier stratosphere [37].

13. It is assumed that, acquisition cost of hydrogen short- and medium-range airplanes will be higher than kerosene airplanes by 12...13 % because of the hydrogen tanks, fuel system, and cost of preceding scientific research [90]. Estimations of operating cost of hydrogen airplanes compared to kerosene ones range considerably: from a slight decrease [75] to a 50 % increase [91], depending on the airplane size, PP type and used technology. But there is a lot of uncertainty in these estimations (service life and maintenance of hydrogen engines and fuel tanks, hydrogen GTE efficiency, variation of hydrogen cost in time) [73]. 14. In 2023, cost of hydrogen (2.5...3.0 $/kg) is 4.7...5.2 times higher than cost of traditional fuel [36]. According to optimistic estimations, after considerable (more than 10 times) increase in hydrogen production (to 2030), it will cost approximately as kerosene does [36]. According to other estimations, hydrogen production from sustainable sources makes it more expensive [92]. It is also necessary to take into account that, hydrogen compression requires 15.5 % of its internal energy content, but liquefaction – 45 % [41].

6. «True zero»

This way means transition to Electric Power Plant (EPP), which is supplied with energy from fuel cells (FC) or electric batteries [16].

Until now, there are only some flyable manned all-electric airplanes (Brditschka MB-E1 (1973), Fishman Electraflyer C (2008, 1 seat), Boeing HK-36 FCD (2008, 1 seat), Yuneec E430 (2009, 2 seat), Siemens/Diamond E-Star (2011, 2 seats), Pipistrel Taurus Electro G2 (2011, 2 seats), Pipistrel Taurus Electro G4 (2011, 4 seats), IFB Stuttgart eGenius (2011, 2 seats), Embry-Riddle Eco-Eagle (2011, 2 seats), Electraflyer ULS (2012, 1 seat), Chip Yates Long ESA (2012, 1 seat), Siemens/Diamond E-Star 2 (2013, 2 seats), Airbus E-Fan (2014, 2 seats), Cambridge SOUL (2014, 1 seat), Pipistrel Alpha Electro (2015, 2 seats), Airbus E-Fan 1.2 (2016, 2 seats), Siemens Extra 300 (2017, 1 seat), NASA X-57 Maxwell (2018, 2 seats), Zero Avia Piper M (2020, 6 seats)), but all of them are light airplanes or even motor gliders [46, 93].

As for bigger airplanes, there are only conceptual designs. In 2022, Airbus reported about development of airplane-prototype with EPP using hydrogen FC with the purpose to determine, is this technology feasible and viable, in order to introduce ZEROe airplane with zero emissions into operation in 2035 [94]. If the aims of tests are reached, the airplane with EPP and FC can carry 100 passengers at distance 1853 km [69].

Common advantages of «true zero» way are as follows:

1. Complete absence of greenhouse gas emissions on-board aircraft [16] (although CO_2 is emitted even during battery recharging [58]).
2. Sustainable sources utilization possibility for battery recharging or hydrogen production on the ground [16]. This also provides independence on fossil energy sources.
3. Low noise level of electric motors [48, 47].
4. Thrust generation by electric motors with propellers/fans, which energized from FC promises efficiency (according to different estimations from 50 % [73] to 55 % [41]) higher, than in case of thrust generation by hydrogen burning in GTE (efficiency near 40 %) [41].
5. Decrease in EPP operation expenses comparing to traditional PP (although it is not a fact yet) [46].
6. Advantages of HEPP (8–13) described in section 4 also suit here.

But this way also requires solving of a lot of problems:

1. Thrust generation by propeller/fan requires development of light electric motors having power 1...10 MW (now the most powerful electric motor generates 0.65 MW) [73].
2. Reaching required properties of batteries [63].
3. Maintaining reliable and safe operation of high voltage electric system at considerable flight altitudes [63].
4. Integration of propulsor, EPP, and airplane systems [63].
5. Drawbacks of HEPP (2–6) considered in section 4 also suit here.

Application of hydrogen with FC gives the following:

1. Liquid hydrogen application, as heat sink allows using superconductive electric motors (thus to increase PP efficiency even more) [73].
2. Specific power of FC can be increased by operating at higher pressure in it, but it leads to mass and complexity increase. Oversizing of FC leads to current density decrease and efficiency increase, so to fuel consumption decrease, but it also results in mass, sizes, and cost of FC increase. New technologies (self-humidifying, transition to high-temperature polymer electrolyte membrane FC) allow increasing in specific power, reduce mass of thermal management system and sensitivity to CO [73].

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

3. Power produced by FC does not depend on flight altitude, but power losses to supply air to FC themselves under optimal pressure increases with the flight altitude. It can offer increasing efficiency at cruising operation mode, but it can limit take-off power. Usually, this PP has electric battery in addition to FC, which works as a buffer at transitional modes [73].

For wide application of FC in aviation, some problems should also be solved:

1. FC can produce contrails more frequently than hydrogen GTE (because the water vapor exhaust temperature is low) [95], but collecting and storing the water vapor emissions on-board airplane results in unsuitable increase in aircraft mass (as mass flow of water vapor produced is nine times the mass flow of hydrogen consumed) [52].

2. Common problems of FC are assumed the following: approximately three times greater mass, high cost, and low service life [73].

3. Problems of polymer electrolyte membrane FC are the following: cooling (necessity of thermal management system [63]), maintaining required humidification, necessity of periodic (in the order of minutes) purging of the anode from nitrogen and water (that leads to losses of some quantity of hydrogen), necessity of hydrogen prior cleaning from carbon monoxide (which poisons the platinum catalyst), expensive catalyst-materials application (such as platinum) [73].

4. Problems of solid-oxide FC are the following: necessity to preheat up to high operating temperature (600...1000 ºC), as a result long start-up time (10...60 min.), limited number of on-off cycles, material operability under these temperatures [73].

E. Adler et al. think that, as EPP with FC provide higher efficiency of hydrogen energy transfer for low power, but they have lower specific power comparing with GTE with hydrogen; then hydrogen GTE are better suits for long-range airplanes, but EPP with FC for short-range ones [73]. According to Boeing, EPP with FC will soon be used for small manned and unmanned aircraft, but not for big passenger airplanes [96].

Discussion and conclusions

1. ***Efficiency***. As far back as in 1940-th, designers of different countries experimented with combined PP. Reciprocating engines were added with atmospheric jet engines driven by reciprocating engines (Caproni-Campini N.1, Caproni-Reggiane Re-2005R, Compini Caccia 42, I-250, Su-5, Yak-9VRDK), ram-jets (La-126PVRD, La-138), pulse-jets (La-7PuVRD, La-9RD), liquid-propellant rocket engines (LPRE) (La-7R, Pe-2RY, Yak-7R, Yak-3RD, Su-7 1944), and later with turbojets (Messerschmitt Me.264, Douglas XB-42, Curtiss F15C, Convair XP-81, North American AJ-1, Ryan FR-1, Convair B-36D, Lockheed P2V). But only the last three airplanes from listed ones were built serially and operated.

The history was repeated in 1950-1960, when already turbojets were added with LPRE (SM-50, E-50, Mirage III with LPRE, Douglas D-558, Saunders Row S.R.53, SNCASO Tridan, Sud-Est S.E.212) or with ram-jets (Leduc 022, North Aviation Griffon). But no one of them was serially built.

A. Boretti stresses that, although hydrogen is the most abundant element in the Universe; however, it is freely available on Earth only in negligible amounts, but splitting the water molecule to produce hydrogen requires huge energy input [97].

HEPP (that is the third way) are actually combined PP, which have well known inherent disadvantages (in case of simultaneous operation of different engine types, it is impossible to ensure their operation in optimal conditions; in case of serial operation, PP has extra mass and sizes), thus inefficiency.

2. ***Technical complexity***. So in 1960-th, it was assumed that, in nearest time almost all new military airplanes would be vertical take-off and landing ones. Great number of projects was developed; a lot of prototypes was tested; but only two of them (Harrier and Yak-38) were run in production due to huge technical complexity.

Complexity level of the third (except parallel HEPP), the fourth, and the fifth ways is estimated as high or very high [16]. This means high technical risks (which usually results in growth of time-frames and expenses for development, or even in impossibility to achieve the goal).

3. ***Economy***. Again in 1960-th, it was assumed that, in nearest time commercial aviation would become supersonic one. In USA, some projects of «hot» (M=3) supersonic passenger airplanes (Boieng-2707, Convair 58-9, Douglas SST, Lockheed L2000) were developed, but fuel crisis of 1970-th brought to nothing these expectations. Only some copies of «cold» (M=2) supersonic passenger airplanes (Ty-144 and Concorde) were built and operated limitedly.

Now, NASA ascertains that, all of NASA's EPP related flight demonstration projects have either experienced or show indications of schedule delays, cost overruns and funding instability [63].

J. Hoelzen et al. conclude that, the targeted emission savings according to the Flightpath 2050 do not seem realistic, when the pollution aspect is viewed from macro-economic perspective [48].

A lot of authors [12, 30, 98], who describe ways 2-5, stress that, transition to sustainable aviation require huge investment in research, development, and infrastructure to become practical and commercially viable option for airlines.

4. ***Ecology***. A. Boretti asserts that, the claim that contrails drastically reduce daily temperature difference by several degrees of Celsius is wrong, and based on the subjective reading of events. Comparing the daily temperature difference in Australian airports (as the most isolated country) from April to December 2019 compared to 2020, and from January to March 2020 compared to 2021, the author notes that, there is no principal difference from drastic flight reduction due to pandemic (approximately by 35 % in average, and by 47 % in the last nine months of 2020). The author concludes that, the implications of contrails on global warming, and their effect on surface temperature, are speculations based on very subjective interpretation of temperature records, and the improper use of never validated computer models; and as the modeling of water emissions is even less reliable than the modeling of CO_2 emission, the decision to progress toward hydrogen-based aviation or not should be based on more solid arguments [99]. Thus even from ecological considerations, the reasonability itself of the fourth and fifth ways raises doubts.

5. Summing up all cited above, it is possible to note that, in case when enough financing is available, 2d-5th ways are very useful to search and develop new ideas and technologies, which can lead to find the sixth, or even the seventh way, which become a mainstream for future commercial aviation. In case when «unlimited» source of money is absent, we have to choose the first way and return to improvement of known technologies, such as, for example, cooling liquid injection in GTE air-gas channel.

Contribution of authors: conceptualization – **Sergii Yepifanov**; review and analysis of information sources – **Ruslan Tsukanov**.

Conflict of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, author ship or otherwise, that could affect the research and its results presented in this paper.

Financing

This study was conducted without financial support.

Data Availability

The manuscript has no associated data.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

All the authors have read and agreed to the published version of this manuscript.

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Надійшла до редакції 05.01.2024, розглянута на редколегії 20.02.2024

АНАЛІЗ ШЛЯХІВ РОЗВИТКУ ЕКОЛОГІЧНОЇ КОМЕРЦІЙНОЇ АВІАЦІЇ

Р. Ю. Цуканов, С. В. Єпіфанов

Предметом вивчення в статті є шляхи зменшення викидів парникових газів комерційною авіацією. **Ціллю** є аналіз відомих з літератури шляхів зменшення викидів парникових газів комерційною авіацією: безперервна еволюція (що містить в собі безліч різних методів для часткового зменшення викидів парникових газів шляхом зменшення витрати палива), «загальний нуль» (що включає в себе методи відшкодування та застосування екологічних авіаційних палив), гібридні електричні силові установки (паралельні, послідовні, послідовно-паралельні, турбоелектричні та частково турбоелектричні), «нуль вуглецю» (заміна згоряння гасу на водень в модифікованих газотурбінних двигунах), «справжній нуль» (перехід на електричні маршові двигуни з водневими паливними елементами або з електричними батареями). **Задачі:** вивчення цих шляхів і виявлення їх переваг та проблем з огляду на ефективність, технічну складність, економіку, екологію та можливість втілення в життя в умовах обмеженого фінансування. Використовуваними **методами** є**:** пошук відповідних джерел в мережі Internet та їх аналіз виходячи з власного досвіду роботи в авіаційній галузі. Отримано наступні **результати.** На основі знайдених джерел інформації стисло викладена інформацію по наявним викидам парникових газів авіаційною галуззю та їх прогнозні значення, коротко нагадано історію розвитку міжнародних угод, щодо обмеження викидів парникових газів, підкреслено актуальність цієї проблеми з огляду на збереження стану довкілля, узагальнено переваги та проблеми, що необхідно вирішити для використання кожного з розглянутих шляхів. **Висновки.** Наукова новизна отриманих результатів складається в наступному: в одній оглядовій статті зібрано інформацію з багатьох літературних джерел, що висвітлює класифікацію, переваги та проблеми, які необхідно подолати для втілення в життя кожного зі шляхів. Шляхом обговорення та історичних аналогій показані додаткові невід'ємні недоліки, що притаманні деяким з цих шляхів (низька ефективність, висока технічна складність, відставання від графіку, перевитрати коштів, нестабільність фінансування, сумнівність в їх доцільності з екологічних міркувань). Намічено напрямок подальших досліджень в цій галузі.

Ключові слова: викиди парникових газів; газотурбінний двигун; шляхи зменшення викидів; екологічні авіаційні палива; гібридні електричні силові установки; воднева авіація; паливні елементи.

Цуканов Руслан Юрійович – старш. викл. каф. проектування літаків і вертольотів, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківській авіаційний інститут», Харків, Україна.

Єпіфанов Сергій Валерійович – д-р техн. наук, проф., зав. каф. конструкцій авіаційних двигунів, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківській авіаційний інститут», Харків, Україна.

Ruslan Tsukanov – Senior Lecturer of Airplane and Helicopter Design Department, National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine,
e-mail: r.tsukanov@khai.edu, ORCID: 0000-0001-8348-8707.

Sergii Yepifanov – Dr. of Sc. in Engineering, Prof., Head of Engine Design Department, National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine,
e-mail: s.yepifanov@khai.edu, ORCID: 0000-0003-0533-9524, Scopus ID: 6506749318.