Opportunities of cryogenic system for hybrid electric propulsion aircraft/solar airship with LH2 and high temperature superconductor

Yury Ravikovich\(^1\), Leonid Ponyaev\(^2\), Dmitry Holoptsev\(^3\) and Rafael Domjan\(^4\)

\(^1\) Head of Engineering Engine Propulsion Power Department, MAI, Moscow, 125983 Russia
\(^2\) Prof. Assistant of Engineering Graphic CADesign Department, MAI, Moscow, 125993 Russia
\(^3\) Head of Engine Propulsion Power R&D Laboratory, MAI, Moscow, 125993 Russia
\(^4\) President, SolarXplorers SA, Rue Galilee 7, CH-1400 Yverdon-les-Bains, Switzerland

Email: yr@mai.ru, plp@mai.ru, mko203@mai.ru, rd@solarstratos.com

Abstract. A comprehensive analysis for research and development (R&D) of the technical appearance and calculation of the technical characteristics of a new hybrid electric propulsion aircraft/solar airship (HEPA) with LH2 and cryocooling system with high temperature superconductivity (HTS) can be used at any stage of the design process of a hybrid electric passenger aircraft in the implementation of the EU FUTPRINT50 international program. A new conceptual synthesis for the creation of an optimal cryogenic cooling system based on the Brayton reverse cycle using turbomachines with basic design schemes for the use of significant cryogenic power with low temperature values has been created for computational mat. models using test thermodynamic models of individual circuit elements, taking into account the efficiency of each element, their hydraulic losses in the lines of all elements of the system: calculation of hydraulic losses in the channel element, thermal control in regenerative heat exchangers with a turbocharger and calculation of a turbo expander. The real-time use of a low-capacity wireless sensor-detector or additional charging components from solar energy based on the Seebeck-Peltier effect will be more effective due to the introduction of graphene structures in the design. Experimental development of a two-stage electric compressor and a turbo expander for demonstration tests of a cryogenic cooling system in the MAI laboratory has been carried out.

1. Introduction

The prospects for the development of new and highly efficient hybrid electric aircraft (HEA) concepts with hybrid electric propulsion (HEP) for regional and long routes airlines are basing on the analysis of the main ‘story’ of the any famous Cryo Aeroprojects and directly related to the use of more profitable cryogenic cooling systems for onboard electrical components and the placement of volumetric tanks of liquid hydrogen (LH2) for Cryoplane project by Germany (in 2000 years), Tupolev TU-136/ TU-155 (in 1990 years) and Wing-Bodyplane project by BOEING (in 1990 years), modern LH2 AIRBUS (in 2020 years) and MAI Aircraft Design Lab (in 2010 years) with copy by DLR Integrating Model in the MAKS Airshow’2019 and additional integrated cover upper surface with nano film solar systems for various aircraft such as Swiss SOLARSTRATOS (in 2010 years) as show on the Fig.1 [1,2,3,4].

For many years, complex scientific research and development in various topical areas have been carried out directly in the MAI laboratories and in the Thermoplane MAI Design Bureau in order to implement mathematical modeling complexes and flight test demonstrator hybrid electric airships Thermoplane MAI.
(40 meters in diameter for flight test in 1990 years) using internal volumes for helium and hydrogen with inhibitory ‘unflammable’ additives that exclude possible explosive risks for various processes of choosing cooling & thermal management systems, taking into account layout, placement and integration design as shown on the Fig.2 [5].

Figure 1. The LH2 Cryoplane projects by Germany (a), TU-136 (b) and AIRBUS (c) with jet and hybrid electric propulsion (HEP) and Solarplane (SOLARSTRATOS Swiss Aircraft) (d)

Figure 2. Disc shaped airship Termoplane MAI projection flight image and design draw and color tentionometry of the cigar and the disk planes
The most advantageous is the use of liquid nitrogen (LN) cooling systems and calculations for liquid hydrogen (LH2) or helium (LHe) and the creation of test demo stands complex for optimizing their operating modes, profitable introduction of electric units based on the use of the effect of high-temperature superconductivity (HTS), which confirmed the importance in the development of the international project FUTPRINT50 in EC and cooperation with CIAM, TsAGI, GosNIIAS and NIC name N. Zhukovsky on the creation of future hybrid electric passenger regional aircraft [6].

2. Development and creation of cryogenic cooling systems for aircraft electrical components

When performing optimization tasks during design analysis, modeling and creation of optimal cryogenic cooling systems (CCS) for on-board electric drives, turbo coolers, energy storage (batteries) and electrical wiring of a hybrid electric propulsion of Cryoplane aircraft [1, 3] based on liquid refrigerants (LN, LHe, LH2) to ensure high efficiency thermal management process of their implementation requires rational approaches and experimental solutions to achieve the best level of transfer-recuperate energy - and the weight return and ensuring the compactness and technological profitability of the equipment based on the high-temperature superconductivity (HTS) effect for minimize 3D sizes and weight HEP aircraft components and solar airship parts.

Various studies at MAI on the design appearance and simulate calculation of the technical characteristics of the cooling component system with HTS for the hybrid electric propulsion of a new aircraft or disk airship can be used for new research with well-known aviation industrial leaders - TsAGI and CIAM. For a mathematical model created using thermodynamic models of individual elements of structural schemes that take into account the efficiency of each element, hydraulic losses in the paths of all elements of the system, and a new version of the architectural scheme of an optimal cryogenic cooling system based on the reverse Brayton cycle using turbomachines was considered, and also with the basic scheme of designing and using cryogenic systems for a given level of cooling performance and the level of temperature difference with a model calculation of hydraulic losses in the channel (pipelines) of a contour element with a heat-protective coating, taking into account the thermal regulation of regenerative heat exchangers with the calculation of turbo charger and turbo expander data. This includes experience in the development of a two-stage neon electric compressor and a turbo expander with a promising high-speed suspension system on gas-dynamic bearings and their testing on the effectiveness of a cryogenic cooling system on the MAI laboratory schematic architecture and test stand-demonstrator picture, as shown on Fig.3 [7].

![Figure 3](image-url)
The selection and analysis of a possible cryogenic system according to the criterion of energy-weight efficiency \( K_{kc_{\text{max}}} \) will be determined by a decrease in the mass of the \( m_{ep} \) electric drive structure due to the use of graphene technologies, which is represented by the mass reduction coefficient \( k_{graf} \), a decrease in the mass of the cryo cooling system of the \( m_{kri} \) batteries through the coefficient \( k_{b} \), and onboard power cables through the coefficient \( k_{k} \), a decrease in the mass of thermal protection of hydrogen tanks \( m_{tk} \) through the coefficient \( k_{tk} \) relative to the take-off weight of the aircraft \( m_{to} \), which can be imagined:

\[
K_{kc_{\text{max}}} = \min \left( k_{graf} m_{ep} + k_{b} m_{kri} + k_{k} m_{kri} + k_{tk} m_{tk} \right) / m_{to},
\]

where \( K_{kc_{\text{max}}} \) for any versions of calculation simulation aircraft/airship model of mass (weight) analysis consist about 0.70-0.75 as perspective graphene technology high efficiency as may special fixing in our conclusion. It’s the main progress point may be confirm the more detail results inside as two previously publications: one from the University of Columbia ‘Measurement of the Elastic Properties and Intrinsic Strength of Monolayer Graphene’ (Science Paper, 2008) [8] and second paper by our joint research with the MAI HTS Electric Lab ‘Superconducting Propulsion System with LH2 Cooling for All-Electric Aircraft’ (J. Phys.: Conf. Ser., 1559, 2020) in the IOP publication [9].

3. The possibilities of local cooling systems using the Seebeck-Peltier effect and highly conductive composite multilayer graphene nano structures

On board the passenger aircraft, various low-power and autonomous electrical systems of sensors, detectors and controllers are provided, spaced over long distances from the main power sources - from engines, batteries and generators - at the ends of the wing, fuselage and tail. At the same time, their power supply can be discrete, but requires electrical wiring. In order to avoid additional costs of weight and weighting of these components, it is possible to use real-time cooling of low-capacity wireless sensors-detectors based on the Seebeck-Peltier effect, which improves the weight return of components for an airplane/airship. This effect consists in the fact that if a constant voltage is applied to two terminals of an electrical circuit consisting of two conductors made of different materials, then one of the contact surfaces will heat up, and the second will cool, i.e. the Seebeck effect gives the recovery of thermal energy into electrical energy and the release of heat.

The Peltier effect is most strongly observed in the case of the use of p- and n-type semiconductors of conductivity. Depending on the direction of the electric current through the contact of semiconductors of different types — p-n and n-p junctions due to the interaction of charges represented by electrons (n) and holes (p), and their recombination, energy is either absorbed or released. As a result of the passage of an electric current of a certain polarity, a temperature difference is formed between the radiators of the Peltier module: one radiator works as a refrigerator, the other radiator heats up and serves to remove heat. If you need to get the maximum delta T up to 150°C, then assemble a cascade of several Peltier batteries.

Figure 4. Peltier cooler system and Graphene technology and efficiency
Devices based on the Peltier effect are extremely reliable, as they have no moving parts and practically do not need maintenance. At the same time, it is possible that their use in combination with additional film-surface cooled charging components from solar energy will be effective due to the introduction of superconducting nano-thin graphene structures in flexible electrical elements and in reinforcement – hardening to obtain lighter composite structures and aircraft assemblies.

4. Application of Peltier cooling system and graphene unique data

a. Thermoelectric cooling is used in various types of detectors, electronic equipment, portable refrigerators and mini-coolers using highly efficient graphene technologies.

b. If cooling devices with high reliability are required, which are placed in small spaces inside the aircraft, for powerful integrated circuits in local thermoelectric coolers of small volumes.

c. Solid-state heat pumps using the Peltier effect are advantageous in thermoelectric cooling devices with elements of graphene structures.

It is necessary to analyze the most advantageous properties and facility of graphene and borophene:

- graphene has a higher electrical conductivity and practically has no resistance, and graphene has 70 times higher electron mobility than silicon. Thus, the mobility of graphene charges is more than 1,000,000 cm²/ V · s. The electron velocity in graphene is 10,000 km/s, although in a conventional conductor the electron velocity is about 100 m/s, it has a high electrical capacity, the specific energy consumption of graphene is approaching 65 kWh/kg. This indicator is 47 times higher than that of lithium-ion batteries, which are so common today;

- it has a high thermal conductivity, it is 10 times more thermally conductive than copper. Its thermal conductivity is about 5000 W / m · K, full optical transparency is characteristic, which is advantageous for thin films of solar cells, it absorbs only 2.3% of light and is optically transparent in a wide range from UV to far-IR, graphene is capable of producing electrical energy, in particular, when the flow of salt water on the graphene sheet, it is able to generate electrical energy by converting the kinetic energy;

- real slim 2D structure of graphene is very flexible and significantly more durable than steel, to lightweight composite mesh and synthetic ropes inside and on top of the aircraft and airships, graphene is the lightest material, it is 6 times lighter than a pen, and under certain conditions graphene activates another ability that allows it to “heal” “holes” in its crystal structure in case of damage, which increases survivability and reliability.

Figure 5. Graphene potential energy efficiency and applications
5. Design and development of integrated circuits of aircraft and airship disks

Comprehensive design analysis and synthesis, modeling and creation of possible variants of cryoplane concepts of various layout schemes (classical and integrated with the Integral Bodyplane MAI and Wing Bodyplane AIRBUS fuselage), taking into account certain difficulties of volumetric placement of heat-shielding tanks for LH2 inside an aircraft as Ecranoplane MAI (in 1980 years) as analogy to the ECIP BLC project (in 1990 years) / solar disk airship (as type Thermoplane MAI) and the addition of energy from film coatings with solar panels similar to the SOLARSTRATOS high altitude flight test project from Switzerland [4, 10]. To choose the layout solutions of a hybrid electric aircraft, it is necessary to take into account the typical conditions and volume-weight differences between liquid hydrogen LH2 and Kerosene in Tab. 1:

| Indicators          | Kerosene | LH2 |
|---------------------|----------|-----|
| Weight (mass)       | 2.8      | 1   |
| Volume              | 1        | 4   |
| Storage temperature |          | -20K|

As part of the research work at MAI, a digital structural and parametric analysis of alternative layouts of any concept of an aircraft of various layout alternatives with the required small or large passenger capacity was carried out, the architecture of which is shown in Fig.6 [11, 12].

The analysis shows the advantages of the layout made according to the above method (HEA-5 flying wing scheme) in comparison with other unconventional schemes and with minor losses for the base aircraft. At the third level, the structural and parametric analysis of the HEA infrastructure shows the geometric shape of the layout in space with various variations:

a) In the tail section or in the upper semicircular superstructure of the cryoplane to accommodate internal fuel tanks in the fuselage; b) A two-body 'bifuselage' design, advantageous for the safety of the cryoplane, with outflow of separate LH2 tanks; c) Disk-body or flying wing combinations, more suitable for the STOL version, f) The use of the rombus-wing or a teardrop-shaped or elliptical fuselage, etc.

![Figure 6. Optimal CAD aircraft design structure for any aerodynamic HEA concept schemes](image-url)
The main task was to minimize the weight of the Cryoplane hybrid electric aircraft (HEA) with increased rigidity at the junction of the wing with the fuselage (as the main problem was identified) and maximize the use of solar electricity due to film solar panels on the surface of the wing and tail. With the positive implementation of the main design strategy and, possibly, future results, this approach is a positive example for innovative research and the development of a new promising international program. New high technologies include new materials - graphene, light alloys and pre-stressed structural analysis for any new integrated HEA body or wing, as well as a solar airship in the form of a disk when analyzing the effectiveness of the design using digital design (CAD/CAM/CAE) to create new hybrid aircraft/large-capacity airships taking into account the permissible aerodynamic modes of deformations and deflections of the wing to transform into add electrical recuperation, as shown in Fig. 7 [12].

![Figure 7. Flow field visualization at take-off & cruise conditions for CAD initial aerodynamic load model with the flexible wing configuration.](image)

Since lightweight thin-walled composite wing structures of a modern passenger aircraft have relatively large aero elastic end deformations and wing oscillation frequencies in flight, as well as during run-up on the runway, the presence of electric piezo-damper systems (EPDS) can give an additional increase in recuperated electricity up to 10-12%, which reduces the level of initial electricity reserve in Li-ion-Graphen batteries of the aircraft and improves the weight return of the aircraft as a whole.

6. Conclusion

The desire to implement new high-performance conceptual solutions in design research when creating hybrid electric aircraft/solar airships and their power plants will be directly interfaced:

- with the implementation of optimal and integrated low-cost cryogenic cooling systems for high-power on-board electric power components (electric motors, electric generators, recuperators and energy storage) with high electrical conductivity and/or superconductivity (power cables, controllers and on-board buses, rechargeable Li-ion batteries and surface nano film solar cells) with new unique materials, including graphene and borophene technologies, which significantly improve specific performance in terms of weight return, strength and compactness;

- with research and experimental verification-testing of new components of cryosystem and verification of complex computational methods of mathematical modeling for the maximum efficiency of these systems when switching from one to another cryosystem - from liquid nitrogen to liquid helium and hydrogen, where hydrogen is also an environmentally friendly fuel, but requires large structural tank spaces and high-quality thermal protection using thin and light-strength highly conductive graphene nanotubes, reducing the mass of structures as $K_{le,max}$ up to 25-30%.
7. References

[1] AIRBUS CRYOPLANE: Liquid Hydrogen Fuelled Aircraft-System Analysis. Technical Report, September 2003.
[2] AIRBUS Zero Family Concepts. Internet Online Aviation News, 21 September 2020.
[3] MAI Science R&D Cryogenic Cooling Systems Reports 2018-2019-2020 Conference papers 2018/2019
[4] Javet R, Domjan R 2018 Pionniers et Aventuriers de L’Energie Solare ISBN: 978-2-8289-1719-7 FAVRE SA, Lausanne, Suisse p 136
[5] Ponyaev L. 1996-97 Thermoplane ALA-40/ALA-600 Catalog Brassey’s World Aircraft & System Directory p 545
[6] Walter A, Ravikovich Yu, Ponyaev L, Holobtsev D etc. 2020 Thermal Management challenges for HEA – FUTPRINT 50, Conference EASN papers, 2-4 September, Italy
[7] Lee C, Wei X, Kysar J W, Hone J 2008 Measurement of the Elastic Properties and Intrinsic Strength of Monolayer Graphene, Science Paper, V.321, pp.385-388
[8] Dezhin D, Dezhina I, Ilyasov R 2020 Superconducting Propulsion System with LH2 Cooling for All-Electric Aircraft / Journal of Physics IOP Conference Series, 1559 012143
[9] EASN Conference presentation of MAI R&D Cryocooling System. September 2020
[10] Ponyaev L. 2018 Scientific LTA Technologies, S&P Journal PSSN 223-2966: Moscow, Russia, Natural & Technical Science 9 pp 60-65
[11] Dolgov O, Kuprikov M, Kuprikov N 2010 Features of detecting the moment-inertial appearance of perspective aircraft in the early stages of design Bulletin of the Moscow Aviation Institute 2 (17) pp 1-4
[12] Ponyaev L 2018 The Periodical Geometry of Engineering Design Principals by use the Optimal Spherical Transformation to the Disc LTA. ST S&P Journal PSSN 223-2966 pp 1-5