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ECONOMIC AND ECOLOGICAL ASPECTS OF THE USE OF NEW CRYOGENIC AVIATION FUELS

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Until recently, the high rates of aircraft engine engineering's development were ensured by the technological solutions improvement and the desire to approximate as much as possible the ideal thermodynamic cycle of turbojet engines. The traditional fuel for turbojet engines is an aviation kerosene – Jet-A fuel group and their regional analogies. The traditional way of aircraft engines efficiency increasing is a raising of a temperature in front of the high-pressure turbine. New alloys and technologies allow to increase the aircraft engines efficiency to a certain level. Raising the temperature in the combustion chamber by 50 degrees increases the efficiency, which leads to a 5% reduction in fuel consumption. However, this approach is technology limited and does not provide innovative solutions. The aircraft engine engineering's development tempo in the 21st century continues to accelerate. The main driver of such processes in recent years is the tightening of economic and environmental requirements. Many aircraft manufacturers are actively looking for ways to reach a new qualitative level in terms of turbojet engines economic efficiency and meeting strict environmental requirements. The paper considers the feasibility of using new cryogenic fuels in aircraft turbojet engines, and possible ways for aircraft industry successful development.

Key words: aviation industry, economic and ecological aspects, aircraft engines, aviation fuels

INTRODUCTION

In the 21st century, the problems of the ecology triggered by aviation transport were identified as priority. In 2016, the International Civil Aviation Organization issued a norm for permissible CO₂ emissions. As early as 2023, these environmental requirements are applicable to new business aircraft with less than 19 seats. These are just the first steps. After 2023, the International Civil Aviation Organization is going to reduce the emissions of nitrogen oxides NO and NO₂, at the level of 5 ... 10 grams per kilogram of fuel. According to these requirements, the International Civil Aviation Organization must provide a CO₂ certification for each aircraft depending on the fuel efficiency criteria. And they, in turn, are determined by the specific fuel consumption of the aircraft engine. As we can see, traditional ways of the problem solution are limited [1]. A fundamentally new solution is needed to reach a qualitatively different level of turbojet engines efficiency. Let us consider possible ways to qualitatively improve the aircraft engines environmental friendliness. The most promising are hybrid power plants, replacing kerosene with biofuels, cryogenic fuels, etc. The cryogenic fuels in aviation were used before. Back in 1936, Robert Goddard tested a mail rocket plane with liquid cryogenic fuel. The Lockheed corporation chose liquid hydrogen as a fuel for the CL-400 Suntan military aircraft in the 1950s. The developers opted for hydrogen because of its combustion stability and low fuel density. Low fuel density demonstrated its negative aspects, since almost the entire volume of the fuselage was allocated for liquid

hydrogen storage and the payload volume was small [2]. The CL-400 Suntan aircraft was powered by Pratt and Whitney engines [3]. In the USSR, hydrogen as a fuel for aircraft engines was used in ground tests of the GTD-350 helicopter engine by the Central Institute of Aviation Motors in 1967. The aircraft engine starting, switching to the nominal operating mode, stable operation of all systems, emergency termination of tests and the transition from kerosene to hydrogen or natural gas were performed. They showed the prospects for hydrogen in civil aviation. The Tu-155 aircraft project was launched in the USSR in 1988 and confirmed the replacing kerosene fuel with liquid hydrogen possibility. The standard Russian aircraft engine NK-8-2U was replaced by an experimental one NK-88. The cryogenic direction was developed further in 1989, when research confirmed the technical possibilities of using liquefied natural gas - the Tu-156 aircraft project. Let's summarize a historical review. The functioning aircraft engines experimental models at the level of 50-60-year-old technologies have shown that the cryogenic fuels in civil aviation use is quite possible. At that time, however, the focus was not on economics and ecology, but on technical and economic indicators [4]. At present, environmental problems have come out on top.

MATERIALS AND METHOD

The authors used a theoretical and practical methods. The main research methodology is a technical and economic analysis of various fuels types use in modern aircraft. A comparative and numerical-symbolic analysis

of various aviation fuels specific physicochemical properties was carried out. Kerosene, liquefied natural gas, methane, propane and hydrogen were compared. The structural and functional analysis of the use of the most environmentally friendly hydrogen fuel was carried out especially carefully. In their research methodology the authors applied the method of scientific synthesis, revealing the deep connections of new types of aviation fuel use in the most modern aircraft both subsonic and supersonic. The theoretical and methodological basis of the scientific research was the integrated application of methods by leading foreign and Russian experts in the field of aerospace technology design and production: structural functionalism, gate system approach, and interactionism. In addition to analytical ones, the authors actively used specific scientific and practical methods of socio-economic research: analysis of documentary sources and the method of statistical data analysis. Information sources used in scientific work include official documents and statistical data; scientific literature on the topic of research and media materials.

A WORKING HYPOTHESIS

The authors used a hypothesis of using alternative environmentally friendly aviation fuels possibility in the aircraft. We recognize the full benefits of hydrogen as an ideal environmentally friendly "green" fuel. But, on basis of careful evaluation of all shortcomings associated with insufficiently developed technological solutions, we propose for the present time to concentrate the engineers, designers and technologist's efforts on the support of methane gas, as an alternative to aviation kerosene. It is liquefied natural gas, from our point of view, that in the near future may be the most optimal aviation fuel from the point of view of both technical, economic and environmental indicators.

RESULTS AND DISCUSSION

As we mentioned above, the International Civil Aviation Organization is focused on ecology and has formulated a target to reduce environmental emissions of CO₂ by 75% and NO, NO₂ by 90% from 2000 to 2050. There is simply no other way for aircraft manufacturers to convert to other environmentally friendly fuels. There are several alternatives to kerosene as aviation fuel - biofuels, propane, methane and hydrogen. Each of these perspective aviation fuels has both advantages and disadvantages. Moreover, the environmental damage from the use of one or another fuel should be assessed not only by environmental pollution during combustion in an aircraft engine, but throughout the entire fuel life cycle of the from its production, transportation, storage to utilization. Ethanol-based biofuels produced from plant or animal feedstocks, organisms' waste or organic industrial waste. Despite the claims of biofuel manufacturers and their potential for aviation, biofuels are not ideal because their cost is several times higher than kerosene. The emission during the combustion is not equal to zero. The production of biofuels still requires additional energy and significant resources [5]. It is worth paying attention to innovative projects of ammonia and hydrogen mixture using as aviation fuel [6]. The authors state that such a mixture is the best alternative to traditional hydrocarbon fuels, because there is no CO₂ as a result of combustion. However, the other emission constituent NO and NO₂ remains. The choice of a perspective cryogenic fuel should be done after an analysis of their thermophysical and thermodynamic properties. The main fuels properties are shown in Table 1. Hydrogen can be highlighted from all other cryogenic fuels because of the hydrogen combustion product is water vapor. Those, absolute environmental friendliness is manifested when burning in the engine.

Table 1: Basic properties of aviation and cryogenic fuels.

	Index	Value			
		TC-1 (kerosene)	Liquefied natural gas (methane)	Hydrogen	Propane
1	Density, kg / m ³ (at temperature, K)	778,6 (288)	424,7 (111)	71,5 (20)	580,0 (230)
2	Calorific value, MJ / kg	43,5	50,0	120,0	45,9
3	Energy intensity, MJ / m ³	33855	21100	8450	26620
4	Cooling resource, kJ / kg	1330	2830	13030	3180
5	Gas constant, J / kg K	57,42	518,26	4124,42	115,24
6	Liquid phase range, K at a pressure of 0.1 MPa	Operational	91...111	14...20	86...230

The second significant advantage of hydrogen is its very wide range - from 4 to 75% - of the hydrogen content in the combustible mixture. Those, a hydrogen engine can operate on both highly lean and, on the contrary, very rich combustion mix [7]. The heat of hydrogen combustion is 2.8 times higher than kerosene. The Liquefied natural gas (LNG) is 17% higher than kerosene. Let's take this analysis critically and consider the disadvantages of hydrogen as an aviation fuel. Liquid hydrogen has more than 10 times less density than kerosene. On the one hand, the use of hydrogen will reduce the take-off weight of the aircraft by 30% [8]. However, the low density of liquid hydrogen is also a big disadvantage. The fuel tank for hydrogen needs to be significantly larger than for kerosene. This fact is principal negative for aircrafts, because of this is corresponded with a many of difficulties, such as necessity to increase the overall aircraft dimensions many times and, accordingly, an increase of aerodynamic drag [9]. Moreover, the specific volume of liquid hydrogen can't be increased via pressure raising tank of liquid hydrogen [10]. Or it will be necessary to significantly reduce the useful volume, which runs counter to the trend of the comfort of air transportation. Another technological challenge for the storage and transportation of liquid hydrogen is its low boiling point. Another alternative to kerosene is gas propane. The gas is obtained during the processing of petroleum products and requires energy to generate it. The main constituent of natural gas is methane. Methane has a calorific value higher than that of propane and kerosene. Natural gas, as the main source of methane, is much cheaper than any other alternative aviation fuel, since its production consists mainly of gas production from the subsurface, purification and transportation to the consumer, and does not require energy consumption for significant chemical and technological processes. After analyzing the thermophysical properties of perspective aviation fuels, we come to the conclusion that liquid hydrogen and liquefied natural gas can become alternatives to kerosene. As we mentioned before, hydrogen does not emit substances harmful to the environment during combustion. liquefied natural gas, while not as environmentally friendly as it burns, nevertheless, liquefied natural gas fulfills the desire of the International Civil Aviation Organization to reduce CO₂ emissions by 20-40% in the next ten years. Hydrogen as a fuel has been already used in prototypes of electric motors for more than one year ago. In 2016, the hydrogen aircraft project HY4 made its maiden flight [11]. The main feature of the HY4 aircraft is its electric engine, which is powered by hydrogen fuel cells. The principle of operation of low-temperature membrane fuel cells with a proton-exchange membrane is to convert chemical energy into electrical one. The hydrogen fuel in the prototype was in a gaseous phase under high pressure. Another company, who create a ZeroAvia followed a similar to the HY4 aircraft way. They aircraft was tested in 2020 [12]. Fuel cells were also installed on the Piper Malibu Mirage aircraft. Hydrogen was also on board in

gaseous phase. The above-mentioned modern prototypes have not gotten rid of the drawbacks caused by the limited thermophysical properties of hydrogen. These aircraft are limited in passenger capacity and engine power, because of fuel tanks occupy a significant internal volume of the aircrafts. The motors used are electric and have limited thrust. Those, now, we can identify another drawback of aircraft hydrogen engines, which is of fundamental importance for passenger aviation. Civil air transport requires a new cryogenic gas turbine unit creation. This goal was declared in 2011 by the European project AHEAD engineers (Advanced Hybrid Engines for Aircraft Development), which began in 2011. The main objective of the AHEAD project was an assessment of creating a promising multi-fuel aircraft with a new hybrid propulsion system feasibility. The AHEAD engineers supposed to use alternative environmentally friendly energy sources, such as liquefied natural gas and liquid hydrogen. In 2020, Airbus corporation introduced the ZEROe program - "Zero emissions" [13]. All three aircrafts of this program should use a hydrogen fuel. Airbus plans to make the first flights of ZEROe in 2035. Research and development work to create a cryogenic fuel aircraft is also being carried out in Russia. So, back in 2018, in Central Aerohydrodynamic Institute named after Professor N.E. Zhukovsky (TsAGI) an aircraft with cryogenic fuel was tested [14]. The main objective of this research was to identify a decrease in aerodynamic quality and directional stability due to an external fuel tank. As we said before, the low density of liquid hydrogen is its serious disadvantage as an aviation fuel, and the external fuel tanks is a logical solution to save useful volume of the aircraft. TsAGI experts suppose, such convertible aircraft can be used for passenger and cargo transportation without structural modifications. According to the given characteristics, the aircraft will be able to carry 50 passengers at a distance of 1500 km or 6 tons of cargo at a distance of 1000 km at a cruising speed of 480 km/h. As seen from Table. 1 the density of LNG is about 8 times higher that liquid hydrogen. Those, when using LNG, problems correspond with low density of hydrogen and necessity to significantly increase the volume of fuel tanks should not exist. We have before said that in order to assess the cryogenic fuels using feasibility, it is necessary to consider the environmental friendliness of not only the combustion process in the combustion chamber, but also the environmental friendliness of the production, transportation and storage of fuel. Moreover, energy costs should also be included here, since the production of energy to support technological processes also damages the environment. Let's compare the processes of hydrogen and methane production based on an economic cost analysis. According to authors [15], the cost of hydrogen production itself is several times higher than that of natural gas production. The use of hydrogen as an efficient fuel also presents other problems. The analysis of such problems is carried out in the article [16], where the authors warn against excessive euphoria of

the future use of hydrogen as an environmentally friendly fuel. In their opinion, the hydrogen mass production will not lead to a significant decrease in its prices. The second drawback is associated with the use of fuel cells as an energy source on board a vehicle. The fact is the fuel cells are relative expensive at the level of modern technologies and their cost remains about USD 7000 1/kW. The service life of fuel cells under conditions of intense operation is several times lower than the service life of a traditional combustion engine. The efficiency of the hydrogen fuel system under these conditions does not exceed 35%. Those, at the level of modern technological solutions, the hydrogen fuel for the electric aviation motor concedes the competitor - aviation turbojet engine. The production cost of hydrogen significantly exceeds the cost of producing LNG, which is already a ready-made natural resource. The LNG production cost is reduced to extraction from the subsoil, filtration and delivery. Hydrogen is not present in nature in the required volumes. Hydrogen production is relative complex, expensive compared to LNG production, and a multivariate process. Today, steam reforming of methane is considered to be a widespread hydrogen production method due to its relatively low cost. Please note that hydrogen is produced from methane, the main constituent of natural gas. Those, methane must be extracted from the subsoil for hydrogen production anyway. Energy costs for the production processes of the reforming reaction are covered by the combustion of the same natural gas. The second most popular way of hydrogen generation is water electrolysis. In this process, water is decomposed by electricity into hydrogen and oxygen. Another method of producing hydrogen is high-temperature electrolysis, when part of the supplied energy is electrical and part of the supplied energy is thermal, which increases the efficiency of the entire electrolysis process [17]. British researchers have analyzed the feasibility of hydrogen practical use as a fuel, using the example of urban public transport [18]. The authors of the study agree that the combustion of hydrogen itself is ecologically ideal. The research has shown that in the methane steam reforming process, one of the waste products of the technological process is carbon dioxide CO₂, against which the efforts of environmentalists are directed. That is, if we consider the environmental friendliness of the process of using hydrogen throughout its life cycle, from its production to oxidation in a power plant, then the whole process cannot be considered environmentally friendly. In another article, the same researchers carried out a comparative analysis of the methods for producing hydrogen by various methods [19]. The authors analyzed steam reforming and electrolysis from solar energy and came to conclusion that the total cost of hydrogen production using a solar electrolysis system is 15 times higher than the natural gas steam reforming cost. It is logical to conclude that the cost of hydrogen produced using solar energy and electrolysis of water will be unacceptable for the mass consumer. And the only relatively cheap method of

hydrogen production today is natural gas steam reforming, i.e. the same methane. The authors of [20] came to similar results. They came to interesting conclusions after analyzing energy sources for natural gas steam reforming. In Australia, the production of hydrogen from brown coal will be slightly cheaper than the production of hydrogen from steam reforming units of natural gas. Those, considering the hydrogen production process itself, we come to the conclusion that modern hydrogen production technologies are either environmentally friendly and very expensive, or relatively inexpensive and environmentally dirty. As you can see, the production of the cheapest hydrogen is by no means an environmentally friendly process, and most likely dirtier than the production of LNG. This is still a fundamental disadvantage of hydrogen due to the limitations of available technologies. Let us consider further the prospects for using LNG. According to the authors [21], in comparison with aviation kerosene produced from oil, LNG has even larger natural reserves than liquid hydrocarbons. LNG also has a wide flammability range. The harmful emissions of NO and NO₂ are about four times lower than that of kerosene. The cost of LNG is several times lower than the aviation kerosene cost. At a storage temperature of 100-110 K in fuel tanks, LNG will be useful for heat removal from energy-intensive aircraft engine units during LNG gasification. The cheapness of natural gas is also confirmed by research [22]. Another advantage of LNG is its physicochemical properties, which provide a more uniform temperature distribution in the combustion chamber during LNG combustion than aviation kerosene [23]. Uniform combustion of LNG also provides more complete oxidation and, as a consequence, less emission of harmful substances [24]. The technological process of LNG production at the level of modern technologies is relatively inexpensive and the most environmentally friendly process. In addition to the production technology, there are scientific and technical challenges for the optimal way of storing hydrogen and LNG on board an aircraft. Obviously, the most suitable method for both LNG and hydrogen is in liquid form. Let's pay attention to the temperature of evaporation at normal atmospheric pressure of the considered fuels. Most civil aircrafts have wing fuel tanks and central fuel tank. The central fuel tank has the largest capacity. It located in fuselage and can be reinforced for LNG storage. For LNG, the temperature level of 100-110 K will not require fundamental changes in the design of aircraft, both from the point of view of the fuel tank location and to ensure their thermal insulation. For liquid hydrogen, the storage temperature must be below 14 K, which requires more effective thermal insulation. The storage temperature can be increased by increasing the pressure in the tanks. The option of storing liquid hydrogen under high pressure is not suitable, since the fuel tanks must be designed for a pressure of 35–70 MPa [25]. The authors of [25] formulated the main difficulties in storing hydrogen fuel:

1. Tanks for storing liquid hydrogen must have a high level of thermal insulation.
2. Fuel tanks with liquid hydrogen must still be pressurized to 2 bar to prevent atmospheric oxygen from entering them.
3. Refueling equipment must prevent air from entering the hydrogen fuel tank, as at the storage temperature of liquid hydrogen, air components are transferred to a solid state and can adversely affect the operation of the entire fuel system.
4. Before pumping liquid hydrogen, a helium atmosphere in tank is required to remove air.

There are other ways of storing hydrogen on board, and not just in its pure chemical form. Chemical methods of hydrogen storage are considered by the authors [10]: they imply the storage of hydrogen in the form of its chemical compounds. For example, in the form of metal hydrides, which are metallic hydrogen compounds. These compounds, with their ability to both absorb and release hydrogen, can be used as hydrogen storage. Unfortunately, at the level of available technology, metal hydrides can hold hydrogen equal to about 5-7% of their weight. And this fact is a serious disadvantage, since the weight of the metal hydride will be too big and unacceptable for an aviation. Carbon nanotubes can also be used to store hydrogen. With regard to aviation, this method is also not yet applicable due to their relatively large mass. Glass microspheres are the most modern method for storing hydrogen. Their disadvantage for aviation application is a technology complexity of their use. Let's summarize the problems of hydrogen storage as aviation fuel. At the level of modern technologies, storage only in liquid form is acceptable, but it is also associated with a number of design tasks for thermal insulation and an increase in the volume of fuel tanks. Another challenge to be addressed in the transition to environmentally friendly cryogenic fuels is the safe aircraft refueling technology and fuel storage at airports. Storage and refueling systems require better thermal insulation to avoid excessive boil-off of cryogenic fuels. For hydrogen, this problem is most urgent due to the liquid hydrogen low boiling point. How serious is the issue of thermal insulation for storing liquid hydrogen is proven by examples. One of such cases of liquid hydrogen tank thermal insulation violation occurred in 2010 in the United States at the John F. Kennedy Space Center. In one of the tanks, anomalously high hydrogen losses were revealed due to a violation of thermal insulation [26]. The unanticipated level of liquid hydrogen boiling off was estimated at 3 cubic meters per day. LNG also has similar storage requirements, but they are less stringent because LNG storage temperature should be at the level of 100-110 K, and not 14 K, as in hydrogen. Let's summarize the main disadvantages of hydrogen as an aviation fuel at the current level of technological capabilities. First, hydrogen costs are higher than LNG costs, both in production and storage. Moreover, hydrogen storage will cost two orders of magnitude

more than for kerosene [27]. The second, most important aspect is ecology, namely, the hydrogen production itself is not environmentally friendly due to the fact that almost all hydrogen is produced by natural gas steam reforming, and CO₂ is the main "waste" of such production. Third, the infrastructure for mass hydrogen production for aviation is not yet developed. The key to the launch and distribution of hydrogen on airplanes is solving storage and production problems and achieving technological progress in this area [28]. LNG cannot be characterized as an absolutely environmentally friendly fuel. In any case, when burned, it loses to hydrogen as an energy efficient and environmentally friendly fuel. Compared to hydrogen, LNG is not nearly as environmentally friendly when burning as hydrogen, but its production, transportation and storage are significantly cheaper and more environmentally friendly. Thus, at the level of modern technologies, the use of LNG is more expedient. Hydrogen as an aviation fuel also has potential and prospects, however, the use of hydrogen fuel will require new technological solutions for its production, transportation and storage.

CONCLUSIONS

Presented research demonstrates utilization alternative environmentally friendly aviation fuels possibility critical analysis. It is shown that, at the level of available technological solutions, the hydrogen utilization is not environmentally friendly. Actually, an alternative to aviation kerosene fuel is LNG. The main component of LNG is methane gas. LNG has a numerous advantage that are undeniable in comparison with liquid hydrogen. LNG has a significantly low production cost, reasonable transportation and storage costs. The second important advantage directly corresponds with designers and engineers' tasks. The specific gravity of LNG very close to kerosene specific gravity. In this case new aircraft can be designed based on available constructive decisions. Hydrogen is, without a doubt, the ideal fuel from an environmental point of view. The replacement of kerosene with liquid hydrogen depends on many exclusively scientific and technological nature problems solving. Until such tasks in the production processes, transportation and storage of liquid hydrogen are resolved, there is no need to talk about the environmental friendliness of hydrogen aviation fuel. No doubt, the environmental norms will become stronger at the global level. Particular attention should be paid to the technological problems solutions, and over time, to new technologies for liquid hydrogen production and storage. This conclusion corresponds to environmental requirements in 10-15 years magnification. Until these liquid hydrogen technological problems are resolved, LNG keep its first place in environmentally friendly aviation fuel.

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