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COMPARATIVE ANALYSIS OF RUSSIAN AND WESTERN APPROACHES TO THE PROBLEM OF ALTERNATIVE FUEL USAGE IN AVIATION

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Abstract

The alternative fuel usage in aviation is one of the responses of air transport and aeronautical industry to the increasingly stiffening ecological requirements. This especially concerns the requirements that are connected with cease of increase and even decrease of the atmospheric emissions of the exhaust products, which are produced by the air transport and contain dangerous and toxic components (carbon and nitrogen oxides, aerosols etc.). The second equally important factor that stipulates the alternative fuel usage in aviation is the constant and rapid soaring of oil fuels prices, which can be observed during the recent decades.

Two different approaches to the solution of the problem of alternative fuel usage in aviation have been developed in the World: “Russian approach” and “Western approach”. They differ from each other due to the following: diversities in the conditions of air transport system operation, discrepancies in the systems of production and provision of the appropriate alternative fuels. The differences in geographic environmental and climatic conditions, structures of economy and aircraft fleets also play an important role. In addition it is also necessary to take into account the stored knowledge, the development experience and the traditions, which exist in the aeronautical industries and air transport of the West and Russia.

1 Problems and challenges

The development of industry and transport, especially during the last 40-50 years, has caused a rapid growth of hydrocarbon fuel consumption. The environmental specialists claim that this has led to significant complications in the environmental situation on Earth. The growth of the hydrocarbon fuel consumption has also led to the increase of the rate of consumption of the non-renewable (depletable) oil reserves. Due to that the global aviation community has formulated a problem of searching for new types of aviation fuels with better ecological and economic characteristics than those of the traditional fuel types. Such new types of fuels should also be manufactured from either inexhaustible raw materials or from the raw materials, which are available in nature in much larger quantities than oil.

Civil aviation industry and airline companies have been actively striving to reduce the emissions of the aviation engines exhaust during the recent decades. During the last 30 years civil aviation has managed to attain a 70% reduction of carbon dioxide (CO_2) emission into the atmosphere normalized to passenger-kilometer.

A process of progressive stiffening of the ecological requirements, which are imposed on the air transport system, is taking place during the recent decades [1]:

- In 2011 NASA has set the following tasks of reduction by 2030 in its forecast document “NASA's goals for a 2030-era aircraft”: reduce CO_2 emission by 70% and reduce the nitrogen oxides (NO_x) emission by 75%;
- The following tasks of reduction by 2050 were set in the New ACARE Vision – “FLIGHTPATH 2050” document, which was

published in 2011: reduce the CO_2 emission by 75% and reduce NO_x emission by 90%.

The increased requirements for CO_2 emission reduction can be fulfilled first of all by the improvement of the aircraft. The efficiency of the traditional configurations of modern aircraft engines and aircraft airframe is getting close to its maximum limit. Radical improvement of their characteristics and reduction of CO_2 emissions is impossible without the development of the alternative engine and aircraft configurations. High hopes are also laid on the usage of the alternative fuel types.

The reduction of fuel prices is also an important task, which is being solved during the creation of the jet fuels that are alternative to the traditional kerosene. The growth of global oil prices during the last decade has resulted in the appropriate increase of the aviation jet fuel prices. At that the high prices of the jet fuel have contributed to the bankruptcy of several airline companies [2].

1.1 The history of usage of alternative fuels in aviation

The activities aimed at searching for new alternative fuels with improved characteristics have started in aviation in the end of 1950-s – beginning of 1960-s. Various types of fuels were analyzed: different synthetic fuels, liquid hydrogen (LH), liquefied natural gas (LNG) - methane, methanol, acetylene, hydrazine, monomethylamine, liquefied propane/butane gas mixes. The following was discovered as a result of the conducted research [3]:

- Synthetic liquid fuels, which are manufactured from bituminous coal or gases, cannot be attributed to ecologically cleaner fuels compared to the traditional kerosene.
- Acetylene, hydrazine, monomethylamine have no advantages over kerosene in terms of calorific value (per *kg*) and costs of synthesis.

All modern and advanced alternative aviation fuels can be divided into two large groups [4]:

- “drop-in” i.e. the fuels, which can replace the standard kerosene without any modernization of the aircraft or its engines. Such fuels can also be used via a “partial replacement” method, which consists in mixing the alternative fuel with the kerosene;
- “non-drop-in”, i.e. the fuels, which cannot be mixed with kerosene or the usage of which requires the modernization of the aircraft and/or engines.

Thus it is necessary to mention that the “drop-in” alternative aviation fuels are gradually introduced into operation at the present time. The replacement is implemented by the methods of mixing the kerosene and “drop-in” alternative aviation fuel.

2 Near-term outlook

2.1 Western approach - biofuels

The “Western approach” to the problem of alternative fuel usage in aviation in the near-term perspective is connected with the usage of the “drop-in” fuels. Alternative fuels of this type include, first of all, the biofuels. At that, the main ecological benefit of the usage of the alternative biofuels in aviation is the decrease of the atmospheric emissions of aerosols and sulphur. Such decrease is only attainable when the appropriate high level of purity of the alternative fuels is provided. Also individual regions display a positive economic result from the usage of “drop-in” fuels, which is connected with the fuel cost savings for the airlines.

According to the IATA forecasts 15% of all aviation fuel will originate from biological sources by 2020. By 2040 the quantity of used biofuel will reach 50% [5]. A number of the biggest global airline companies have already launched their programs connected with the usage of biofuel and conduct the appropriate test flights.

2.2 Problems and prospects of manufacturing and usage of biofuel

Today the main part of biofuel is produced from grain crops. These grain crops cannot be produced in the quantities, which are required for the needs of modern aviation. Thus the biofuels, which are produced from sea weed, are studied intensively. Sea weed can give 15 times bigger “fuel harvest” compared to grain crops.

Alternative biofuels decrease the negative ecological impact mainly due to the processing of CO_2 during the growth of the biomass (standing crop). Therefore, if the whole “life cycle” of the biofuel is taken into the account, it is possible to conclude that CO_2, which is emitted during the fuel combustion, is compensated by CO_2, which was absorbed earlier.

The research, which was carried out by scientists from MIT and RAND Corporation [2], as well as Boeing, NASA and MTU Aero Engines [6], has noted the following important problem, which limits the usage of biofuel: its freezing point is high and it dissolves during long-term storing (several months).

The increase of bioproduct prices could be a hindrance to the wide spreading of biofuels. Such price change would be connected with the growth of the demand for food products, which would be linked to the increase of the Earth population. According to the forecasts the Earth population size will reach 10 billion people by 2050.

2.3 Russian approach - liquefied propane/butane gas mixtures

Russian approach to the problem of alternative fuels usage in aviation in near-term perspective is connected with the usage of propane/butane gas mixtures (liquefied aviation fuel (LAF)). The propane/butane gas mixtures should be obtained from the associated petroleum gases (APG) or during the natural gas stripping. Such process implies the obtaining of the following ecological benefits: decrease of the emissions of carbon oxides, nitrogen oxides and aerosols into the atmosphere during the combustion of LAF in the aircraft engines; prevention of the APG flaring during their disposal. However, there are also economic benefits that can be expected, first of all, in the oil production regions.

LAF is a mixture of hydrocarbons [7]:

- ethane C_2H_6 – 0…2%,
- propane C_3H_8 – 0…25%,
- butane C_4H_{10} – 45…50%,
- pentane C_5H_{12} – 30…20%,
- hexane C_6H_{14} – 10…3%.

The Table adduces the comparison of the calorific value (per *kg*) and density of aviation kerosene and LAF.

Table. Calorific value (per *kg*) and density of aviation kerosene and LAF [7]

Fuel characteristics	Aviation kerosene	LAF
Calorific value, *kilocalorie/kg*	10 300 -10 250	10 940 -10 860
Density, kg/m^3	775	595-618

LAF usage requires minor modernization of the onboard subsystems and engines of the aircraft. At that it is necessary to provide for the usage of kerosene both in separate tanks as well as mixed with LAF.

The technology of LAF production consists in extraction of the fractions with the appropriate hydrocarbon composition from the heavy component of the associated petroleum gas or natural gas. It can easily fit into the traditional technological layout of the gas processing. Thus such technology can be implemented on all gas processing plants of the Russian oil and gas industry.

It makes most economic sense to produce LAF at the large gas processing plants that are available in the developed gas and oil production regions. However, it also makes economic sense to use small-scale mobile skid-mounted gas-processing unit plants in the newly developed distant and hard-to-reach regions of gas and oil production (North and Syberia). One unit plant of this type with the weight of no more than 3 tons provides enough fuel during a year for 15-20 Mil-8TG helicopters [7]. At that the maximum price of one ton of LAF does not exceed 50 USD.

3 Long-term perspectives

3.1 Cryogenic fuels

Both Western and Russian approaches to the problem of usage of alternative fuels in aviation in long-term perspective are connected with the employment of cryogenic fuels: LNG and LH. Utilization of such types of alternative fuel in aviation implies both ecological and economic benefits. The usage of LH is especially beneficial in terms of ecology. Economic benefits can be attained due to the relative cheapness of the natural gas. Further benefits can be obtained in the future on the condition that the problem of cheap LH production is solved.

Usage of cryogenic fuels requires substantial modernization of several aircraft onboard subsystems and engines. In this case the creation of a new designated aircraft with engines that use cryogenic fuel will produce a much better effect. At that, the projects of such aircraft also provide for an opportunity to use the kerosene, which would be stored in the separate tanks. This kerosene could be used in combination with the cryogenic fuels during the individual stages of flight or when the cryogenic fuels are unavailable at the refueling airdrome.

The research, which was conducted in Russia, has shown that the introduction of cryogenic fuels would require solving many complex problems at all stages of the aircraft life-cycle. This would include creation of:

- fire and explosion safety system,
- fuel leak detection system,
- cryogenic fuel system,
- systems of the fuel tank pressurization,
- engine start system,
- thermal protection systems for aircraft structure,
- cryogenic refueling equipment,
- equipment for prolonged storage of cryogenic fuel.

4 Gas fuels

4.1 Comparison of liquefied gas fuels

Two types of liquefied gas fuels are used:

- LNG, which consists mostly out of methane (in Russia there are enough gas reserves for more than 150-200 years);
- propane/butane gas mixes – LAF.

Historically the fuel, which is produced out of propane/butane, was the first to gain widespread. Its advantage consists in the fact that it can easily be liquefied at normal temperature and pressure of only 1.0-1.5 atmospheres.

Methane can only be liquefied at very low temperatures (around -160^{o}C). The appropriate liquefaction technologies are not cheap. Methane can also be compressed, but the required pressure equals 200-250 atmospheres. This means that the cylinders should be strong and heavy. The safety requirements during operation of aircraft with methane are much higher than the requirements during operation of aircraft with propane-butane.

Global manufacturing of LNG is developing at a rapid pace. The volumes of global LNG sales have grown by 110 times during the last 40 years. According to the forecasts these volumes will increase by 7% each year during the following ten years.

4.2 Liquid hydrogen

Liquid hydrogen (LH) is a cleaner fuel from the ecological point of view than kerosene [3]. Water is its main combustion product. However, the combustion of 1 kg of hydrogen produces 1.5 times more nitrogen oxides NO_x than the combustion of 1 *kg* of kerosene. Such difference is connected with the fact that hydrogen combustion temperature is 2508^{o}K and kerosene combustion temperature is 2335^{o}K. However, this is compensated by a much higher calorific value of the hydrogen (28660 *Kcal/kg* for hydrogen; 10250 *Kcal/kg* for kerosene). Therefore the emission of nitrogen oxides per unit of thrust multiplied by unit of time during hydrogen combustion will be by 1.85 times lower than that of kerosene.

The experiments that were carried out in Russia in 1990s have shown the following: the reduction of time, during which the hydrogen-air mixture is present in the engine combustion chamber, decreases the emission of NO_x significantly. The results of these experiments were confirmed by foreign scientists. The tests were carried out for a combustion chamber with the length of the flame tube, which was reduced by two times compared to normal. These tests have shown that such chamber provides two times less emission of nitrogen oxides NO_x.

Taking the abovementioned into the account it is possible to expect the reduction of the nitrogen oxides NO_x emission by the hydrogen aircraft engines down to 1…3 *g/(kg of fuel)*. The emission of nitrogen oxides NO_x for modern kerosene engines is equal to 12...15 *g/(kg of fuel)*.

Russian and foreign scientists have proven experimentally that the reduction of the combustion temperature allows for a reduction of nitrogen oxides NO_x emission. Such reduction requires combustion of gas mixture instead of liquid-phase drop mixture. Special burner nozzles and combustion chambers were developed and tested on the stands to attain this goal.

The experience of Russian research and development has shown that the usage of liquid hydrogen and LNG provides for the creation of an ecologically cleaner gas-turbine engine even in the cases when a combustion chamber with a traditional structure or its slightly modified version is used [8].

The experience of the conducted research has shown that the lesser density of cryogenic fuels requires the placement of large ball-shaped or cylindrical fuel tanks onboard the airplane. This results in the increase of the overall dimensions of the “cryogenic” aircraft and degradation of its performance. The degradation happens due to the growth of the drag of the airplane and reduction of its lift-to-drag ratio by 10…18%. However, the usage of liquid hydrogen for cooling of the engine components allows for additional increase of its specific thrust (thrust-to-weight-of-the-engine ratio) by 10…13% and reduction of its dimensions by 5…6% [8].

Analysis has shown that the advantages of the liquid hydrogen as aviation fuel prevail over its shortcomings [8]. Thus even despite the degradation of the performance of the “hydrogen” airplane it nevertheless still has advantages over the “kerosene” one in terms of fuel quantity by 64…75%, weight of the airplane by 25…51% and engine thrust by 12…49%. All of these advantages are attained due to the high calorific value of the hydrogen.

The research, which was conducted in Russia and abroad, has shown [8] that fire hazards of the liquid hydrogen in emergency situations are even smaller than those occurring during leaks of the similar quantity of kerosene. Such phenomenon is explained by high vaporizability of the liquid hydrogen. If the system leakproofness requirements are met and safety regulations are observed, the requirements imposed on the operation of liquid hydrogen are not stiffer than those imposed on operation of aviation gasoline.

However, it is necessary to note an important condition: it is only possible to expect mass use of liquid hydrogen in aviation in the case of availability of a huge quantity of cheap and ecologically clean energy, which is required for its production [9].

5 Design of aircraft, which use alternative fuels

5.1 Design of airplanes with liquid hydrogen engines

The first projects of airplanes with turbojet LH engines (Lockheed CL-400) and first flight test experiments with such airplanes (B-58) were carried out in the second half of 1950s. The first airplane with a LH engine, which worked during several dozen successful test flights, was developed in Russia by a Russian airplane design bureau n.a. Tupolev. It was a modernized version of the Tupolev-154 passenger airplane – Tupolev-155 airplane. Tupolev-155 was equipped with a specially modernized engine, which was developed by engine design bureau n.a. Kuznetsov – NK-88.

One of the important urges for the development of the technologies of LH application as an aviation fuel originated from the headship of the Academy of Sciences (AS) of USSR [3]. In the beginning of 1970s headship of AS announced that by the end of 1970s the cheap LH would be produced in USSR in large quantities. Based on these forecasts the Minister of Aviation Industry of USSR has given the permission to start the activities on the research of the possibility of usage of LH as fuel for aviation gas-turbine engines. However, in the first half of 1980s it became clear that the forecasts of AS of USSR concerning the rapid creation of the technologies for manufacturing of cheap LH, were erroneous.

Intensive research on the application of liquid hydrogen in aviation has been carried out in the Western countries for almost 40 years (with some interruptions). A significant urge for carrying out such activities originated because of the energy crisis of 1970s and increase of the aviation kerosene prices. However, at present the cryogenic fuel is first of all considered as the important measure for the improvement of the ecological situation.

Big research activities on the usage of cryogenic fuels on the airplanes are carried out in Germany by DASA Company. German specialists have been collaborating with the Russian design bureau OKB n.a. Tupolev in the first half of 1990s.

Research on the problems of application of LH as fuel for transport airplane has been resumed in European countries in the beginning of 2000s [10]. European Commission has allocated funding for the research of the "Cryoplane" project in 2000. As a result of the conducted research it was found that the LH airplane configuration requires substantial changes compared to that of the kerosene airplane. The LH airplane should have the following specific features:

- large cylindrical tanks for LH with thick thermal isolation;
- engines with modernized systems of hydrogen fuel supply and combustion chambers;
- modernized fuel system;
- modernized structure of the airplane airframe.

The publication [6] (Boeing, NASA, MTU Aero Engines) adduces the comparison of the projects of short- and long-range trunk-route airplanes according to the fuel efficiency criteria (*pass.-km/fuel consumption unit*) for the usage of LH fuel, compared to the usage of kerosene:

- a reduction by 28% was obtained for the short-range airplane (500 *nautical miles*) for the LH usage case;
- a reduction by 2% was obtained for the long-range airplane (3 000 *nautical miles*) for the LH usage case;

The conducted research has shown that to use LH in engines it is necessary to modify the combustion chamber (first of all, to reduce NO_x emissions) and the fuel system elements (pumps, fuel supply lines, engine control equipment) as well as use the heat exchanger for LH vaporization and heating.

Russian and foreign research has also shown that LH usage would influence the airfield infrastructure, especially the fuel storage and filling systems, as well as the hangar ventilation system.

5.2 Design of airplanes with liquefied hydrocarbon gas engines

New work was commenced after the activities on the hydrogen engines and airplanes were put on hold in Russia. Starting from the first half of 1980s the research on the problems of application of LNG as alternative fuel for aviation began. The first stage of the research provided for the possibility of operating the engine both on LNG and kerosene. This means that a double-fuel engine supply system was created.

The tests of the NK-89 experimental engine on LNG (modernized version of NK-88 engine on LH) have started in 1986. Since all systems of the engine were designed for LH, they could have been used for LNG, the boiling temperature of which is by 100 degrees higher than the boiling temperature of liquid hydrogen. The fuel (LNG) is supplied into the combustion zone of the developed NK-89 engine in gaseous state. The combustion of LNG results in lower level of CO_2 emission compared to the kerosene combustion and total absence of soot. Lower flame temperature during the LNG combustion ($2287^{o}K$) compared to kerosene combustion ($2335^{o}K$) induces lower emission of NO_x. Russian research has shown that the transfer from kerosene to LNG decreases the concentration of nitrogen oxides in the exhaust gases by 30%. If higher calorific value of LNG is also taken into the account, it is easy to see that the required quantity of fuel is decreased even more. This leads to a further decrease of the amount of NO_x emissions per unit of created thrust per unit of time by 10% more.

Gaseous state of LNG allows the designers to attain a high degree of the mixture homogeneity. The usage of this quality requires the creation of special combustion chambers, which provide a high degree of the air-LNG mixture homogeneity. This allows to combust “lean” mixtures and thus additionally decrease the polluting emissions by 1.5…2 times.

Moscow Aviation Institute (MAI), Central Institute of Aviation Motor-building (CIAM-TsIAM) and Air Force Engineering Academy (AFEA) n.a. Zhukovsky have conducted research on the effectiveness of cargo airplanes on alternative types of gas fuels [11, 12]. To solve this problem a mathematical model of the “Aircraft-Engine-Fuel” system was created. An optimal composition of the LAF was determined. This composition was selected based on the condition that LAF should stay in liquid state in the whole range of the flight modes that are attained during the airplane operation (flight envelope). At that no substantial modifications of the fuel system structure are required. The amounts of the carbon dioxide emission were calculated and the transport efficiency (fuel consumption per ton-kilometer) of cargo airplanes was evaluated. The evaluation was carried out for Il’ushin-214T (project), Il’ushin -76 and Antonov-124 cargo airplanes (with maximum take-off weights of 20, 40 and 120 *tons*). The calculations were made for the cases of usage of various types of alternative fuel: liquefied natural gas (LNG) and liquefied aviation gas fuel (LAF). The results have demonstrated that the type of used fuel determines the specific features of the structure and parameters of the optimized engine. The optimization problem was solved for two types of statement:

- for constant take-off weight of the airplane;
- for minimization of the airplane take-off weight.

The placement of all fuel in integral wing tanks (in the wing torsion boxes) in liquid state at air standard conditions was considered as an option for the usage of TS-1 kerosene and LAF. A configuration version with an external fuel tank over the fuselage was considered for the usage of LNG. Such external fuel tanks over the fuselage would increase the drag and weight of the airplane airframe (a version without wing fuel tanks was considered for the usage of LNG).

During the research it was established that the properties of the alternative fuel determine the optimal structure and parameters of the airplane and engines substantially. As a result of the conducted research it was established that compared to the usage of kerosene the following happens [11]:

- When LAF is used the airplanes retain their fuel efficiency value, decrease the CO_2 emission by 3…4%, at that there is no sulfur or soot emission, the cost of the flight hour decreases by 1.5 times as well, the take-off weight of the airplanes decreases by 3…5%.
- When LNG is used, CO_2 emission is decreased by 17%.

5.3 Tupolev-155 airplane with NK-88 engine

NK-8-2 serially manufactured turbofan engine with the thrust of 10500 kg was used at the first stage for the solution of the problem of cryogenic fuel (liquid hydrogen) usage. It was modernized for the usage of a new type of fuel – liquid hydrogen. At that the gas-air flow duct, engine configuration and engine accessory gear box were left without any changes.

Tupolev-155 experimental airplane (converted serially manufactured Tupolev-154B passenger airplane) was equipped with only one engine on hydrogen (in the right nacelle) (Fig. 1). Two other engines were working on kerosene.

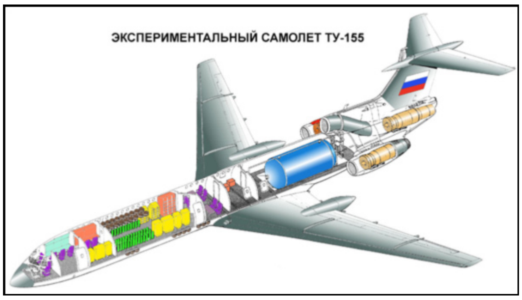

Fig.1 Tupolev-155 airplane layout.

A special tank for cryogenic fuel was placed in the tail part of the fuselage. The tank was placed in the place of a passenger cabin. It was isolated from the adjacent fuselage sections by buffer zones, which were equipped with a ventilation system. The special tank for the cryogenic fuel (liquid hydrogen) had the volume of 20 m^3 with a reinforced insulation of thermal blanket (vacuum-screen) type. The hydrogen can be stored in such tank at the temperature lower than 253^oC. It was supplied to the engines by a special turbopump assembly. A special helium control system was created to control the engine accessories.

Tupolev-155 airplane made its first flight on liquid hydrogen on 15 of April 1988. Its first flight on LNG took place on 18 of January 1989. After the flight tests and retrofit modifications were completed, Tupolev-155 airplane made a number of demonstration flights abroad:

- in October 1989 – on the route of Moscow – Bratislava – Nice;
- in May 1990 onto the aviation exhibition in Hannover (FRG);
- in 1991 – to Berlin.

The tests have shown that the fuel (LNG) consumption has decreased by almost 15% compared to kerosene. The experience of Tupolev-155 airplane operation has shown that the usage of cryogenic fuels is even safer than the usage of aviation kerosene [13]. Even a small leak of cryogenic fuel can be detected by gasometry. After that it is possible to immediately take the actions for prevention of inflammation. Unlike the kerosene tanks, the cryogenic fuel tanks are not explosion hazardous because there is no oxygen in them. After leakage the cryogenic fuel rapidly vaporizes and volatilizes.

5.4 Mil-8TG helicopter

Today in the World there is only one example of the creation of an aircraft on LAF – the Mil-8TG helicopter (Fig. 2). Helicopter design bureau n.a. Mil has started the development of the Mil-8T version on LAF in 1982. The bench tests of the TV2-117TG modified helicopter engine were carried out in 1985. The first successful flight tests of the Mil-8TG helicopter were carried out in 1987-1988.

Fig. 2 Mil-8TG helicopter.

To provide for the usage of LAF on the helicopter its fuel system was modernized. In particular, bigger fuel tanks were installed as the calorific value per unit of volume is slightly less for LAF than for kerosene (Table) [7]. Besides, the saturated vapor pressure of LAF exceeds atmospheric pressure at positive temperatures. All of the abovementioned results in the increase of the helicopter empty weight due to the increase of the fuel system weight.

The increase of the fuel tanks size leads to an increase of the projected helicopter area on the horizontal plane. This, in turn, increases the main rotor lift losses due to the downwash of fuselage and tanks during vertical take-off and hovering. If the main rotor lift stays constant, this leads to a slight decrease of the maximum take-off weight of the helicopter. The increase of the LAF fuel tanks size increases the helicopter drag, which decreases its cruise speed (from 225 *kph* down to 220 *kph* or by 2% for Mil-8TG helicopter) [7].

The placement of the fuel tanks on special trusses and other structural solutions provide safety for the crew and passengers in case of emergency landing. The equipment also includes additional devices (gas detectors) for detection of gas leaks in the cockpit, cargo hold and engine compartment.

Specific features of Mil-8TG helicopter structure compared to the Mil-8T base version:

- TV2-117TG engines work on LAF or kerosene as well as on the mixture of these fuel types. The engines almost were not modernized. Only the automatic control system was modified. It was equipped with a gas feed pump, a gas flow adjuster and a fuel type feed (gas to kerosene) switch [14].
- Mil-8TG helicopter (compared to Mil-8T) was additionally equipped with two external

fuel tanks with the total volume of 2000 liters [14]. A fuel tank with aviation kerosene was left on the helicopter as en-route fuel reserve. External fuel tanks can also be filled with kerosene, when there is no gas in the airport. It is even possible to refuel (replenish the fuel supply) with kerosene as LAF mixes with kerosene extremely well. Specific weight of the structure (weight of the structure per unit of fuel volume) is equal to 0.05 *kg/l*. The cylindrical fuel tank is leakproof. It is equipped with a closed drain and designed for operating pressure of up to 1 MPa [15]. The fuel tanks are constructed as reservoirs out of metallic foil, which is wound by glass fiber with 2.5 mm thickness. The safety factor of the structure is equal to 3, which fully complies with the certification requirements.

The engine start on kerosene was preserved to simplify the modification of the Mil-8TG base version helicopter. The pilot switches the engine to gas after the check, takes off, fulfills the flight mission, and switches it back to kerosene after landing.

Main results of Mil-8TG tests [14]:

- Flight personnel noticed no difference in piloting the helicopter and operation of its engines compared with the “kerosene” prototype.
- The engine could be started at the first attempt at low temperatures.
- The exhaust is clean (no soot).
- There was no combustion residue on the combustion chamber walls and turbine blades (this helps to increase the engine service life).
- Specific fuel consumption per unit of power is lower by 5% due to the higher calorific value of the gas.

According to the estimations of the specialists [14] the modernization of the engine and helicopter is rather simple. If the appropriate components are available, the serially manufactured helicopter can be re-equipped at any aircraft repair plant (or another industrial establishment) during the scheduled maintenance. The modification of one Mil-8 helicopter would cost around 100 000 US Dollars. The calculations and test results have shown that the usage of LAF on Mil-8T helicopter instead of kerosene would allow its owner to decrease the operational costs of the helicopter by 25-30% [13].

The usage of LAF on the helicopters is promising in the oil- and gas-producing regions of the North and Siberia. This is especially true for the newly developed regions with under-developed road infrastructure. In such regions there is an excessive abundance of associated petroleum gas while the aviation kerosene is rather expensive and there are problems connected with its delivery [14].

5.5 Russian airplane projects on alternative fuels

Active research, which is devoted to the problems of creation and operation of aircraft on alternative fuels, is carried out in Russian scientific and design organizations as well as Universities during the last 20 years.

The results of the research, which was carried out in CIAM-TsIAM, Central Aero-Hydro-Dynamic Institute (CAHDI-TsAGI), State Research Institute of Civil Aviation (SRI CA-GosNII GA) as well as design bureaus n.a. Il’ushin and n.a. Yakovlev, have demonstrated the possibility and effectiveness of the conversion of both helicopters and airplanes to LAF [9]. At that the LAF with low content of propane can be loaded directly into the wing fuel tanks of the commuter airplanes like Il’ushin-114, Yakovlev-40 and others, if the outside air temperature on the ground does not exceed +5°*C*. Such temperatures can persist in some regions of Siberia and North for up to 10 months in a year. It is obvious that to provide for a possibility of LAF loading into the airplane wing tanks at all values of the outside air temperature on the ground, which are specified in the certification requirements (-50°…+50°*C*), it is necessary to reinforce the fuel tanks to provide for the excessive pressure of up to 1.0 *MPa* in them.

A special initiative program for the creation of the airplanes on cryogenic fuels was developed in design bureau n.a. Tupolev [3, 16, 17, 18, 19]. Tupolev-156 cargo-passenger airplane with NK-89 engines on LNG (Fig.3) should be created at the first stage of this program [13]. Preliminary project of the Tupolev-156 airplane was developed and more than 70% of the drafts of the detail project and technical documentation for manufacturing was produced.

Fig. 3 Tupolev-156 airplane layout.

The experience of the Tupolev-156 airplane development (first of all, the experience of development of a cryogenic fuel system for LNG) was used for a number of new projects of design bureau n.a. Tupolev:

- Tupolev-204K medium-range trunk-route passenger airplane with PS-92 engines on LNG (Fig.4). This airplane was built on the base of Tupolev-204 airplane with PS-90A engines. The kerosene is placed in wing fuel tanks, the fuel tanks with LNG are placed on the fuselage in a special fairing. The airplane will carry 210 passengers over the distance of up to 5 200 *km*. The fuel efficiency of Tupolev-204K airplane should improve by 4-5% compared with the Tupolev-204 airplane.

Fig. 4. Tupolev-204K model.

- The Tupolev-136 regional cargo-passenger airplane with two TV7-117SF engines. The layout of this airplane takes into account the usage of LNG (Fig. 5). Tupolev-136 has a take-off weight of 20 *tons* and can transport 53 passengers or up to 5 *tons* of cargo over the distances of up to 2200 *km* with the speed of 550 *kph*. Fuel efficiency of the airplane is about 20 *grams/(passenger×km)*. The usage of LNG would provide for the reduction of the direct operational costs by 30%. A version of the airplane on liquid hydrogen is also researched.

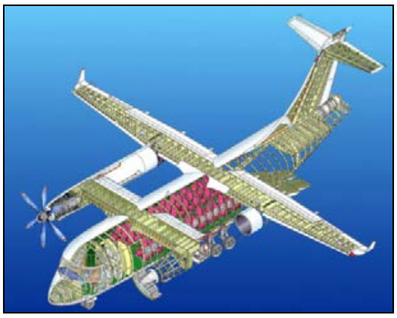

Fig. 5. Tupolev-136 layout.

- Tupolev-330K transport airplane with NK-94 engines on LNG (Fig.6). The airplane is intended for transportation of cargo with the weight of up to 35 *tons*. The kerosene on the airplane is placed in wing fuel tanks. The LNG fuel tanks are placed on the upper part of the fuselage in fairings, which are shaped to minimize the aerodynamic drag. NK-94 engine is a cryogenic version of the NK-93 engine.

Fig. 6. Tupolev-330K model.

- Tupolev-334K short-range trunk-route passenger airplane with BR-710C engines on LNG (Fig.7). Tupolev-334K was created on the base of Tupolev-334 airplane. It can transport 102 passengers over the distances of up to 2 000 *km*.

Fig. 7. Tupolev-334K model.

The following estimations of the performance of the airplanes on LNG in comparison with the airplanes on traditional kerosene fuel were obtained as a result of the research, which was conducted by design bureau n.a. Tupolev [20]:

- The modification of the existing “kerosene” airplanes for the usage of LNG would result in the increase of their take-off weight by 5…9%. At that the value of their fuel efficiency (fuel consumption per passenger-kilometer) would remain unchanged.
- The airplane, which was specially designed with taking into account the usage of LNG, can have its fuel efficiency (fuel consumption per passenger-kilometer) improved by up to 12% compared with its equivalent that uses traditional kerosene fuel.

According to the estimation of JSC “Tupolev” specialists [20] it is expected to see a substantial reduction of the combustor discharge emission when LNG is used on the airplanes compared with the airplanes on kerosene fuel:

- of the carbon oxide by 5-10 times,
- of the nitrogen oxides by 1,5-2 times,
- of the polycyclic aromatic hydrocarbons by 10 times.

6 Conclusions

A lot of activities aimed at the search for alternative fuels for air transport are conducted in Russia, European countries and USA during the last 25-30 years. All of these activities can be divided into two groups: search for fuels in near-term and long-term future.

The alternative fuels of “drop-in” type are considered for the near-term future: in USA and European countries the “drop-in” fuels primarily imply biofuels (which are already being introduced into day-by-day operation), while in Russia “drop-in” fuels imply liquefied propane-butane gas mixtures (liquefied aviation fuel - LAF).

Only cryogenic fuels are considered for long-term future: in Russia those primarily include liquefied natural gas (LNG) – methane and liquid hydrogen (LH), while in European countries “cryogenic fuels” imply primarily only liquid hydrogen.

A set of experimental activities on the usage of alternative fuels (LH, LNG, LAF) was conducted in Russia. The appropriate versions of engines and aircraft (Tupolev-155 airplane and Mil-8TG helicopter) were created during these activities. These aircraft and engine versions have completed the flight tests successfully and demonstrated the feasibility of the implementation of the proposed concepts from the engineering point of view. They have also shown the economic and ecological efficiency of the abovementioned concepts. The results of the activities on the creation of these aircraft as well as the research that accompanied these activities allowed formulating some common approaches and foundations of the design of aircraft, which use the alternative fuels.

The theoretical research on the alternative fuels has demonstrated contradicting results, which were obtained by various researchers. This indicates the necessity to continue and elaborate the appropriate in-depth studies.

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