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ANALYSIS OF ROCKET FUELS AND PROBLEMS OF THEIR APPLICATION ON THE EXAMPLE OF UKRAINE

The object of research is the problems of rocket fuel application, the state of art and prospects. These problems are characteristic of almost the entire range of brands of modern rocket fuels suitable for application. These are problems with the basic physic-chemical and operational properties, technical requirements for the quality of rocket fuel, problems with the functioning of the refueling infrastructure, as well as ensuring the purity of rocket fuels.

Given the ban on the use of highly toxic poisonous rocket fuels based on nitric acid, there is a problem of replacing them with less toxic. This problem is aggravated by the lack of production of their own petroleum-based hydrocarbon rocket fuels in many countries. In general, it leads to acute problems with the supplying spacecraft and rocket carriers with rocket fuels. In particular, such a problem arises in Ukraine with Ukrainian-made missiles.

The constant attention to the problem of the aviation and rocket fuels quality results from many factors. The research has used a comprehensive approach to fuel quality assessment, analysis of world experience, synthesis of results and retrospectives, historical-evolutionary and logical approach. High level of fuels purity provides high reliability, safety of flights, increases technical resource of engine units. Therefore, expenses for achievement and maintenance of necessary level of purity of fuel and working liquids are quite justified.

The result of the research is a classification of liquid rocket fuels based on their component composition and chemical structure. Requirements to energy, kinetic, operational characteristics, ecological and economic properties of liquid rocket fuels (LRF) are formulated. Given the unsatisfactory environmental conditions, the use of kerosene as a rocket fuel is more relevant compared to heptyl rocket fuel. Jet fuels T-1, T-6, T-8B are well suited for space technology of many countries, but very few countries can produce them. Purchasing in neighboring countries is not always possible for a number of reasons. Comparative analysis shows that liquid rocket fuel RP-1 in most respects is an analogue of jet fuel T-1 and T-6 and can be used as a substitute for rocket carriers. However, the problem of development of standards and regulations on quality control of LRF during their storage and operation is not solved. In particular, there is no clear regulation for the process of refueling LRF missiles at low temperatures. There are no regulations on the content of free and dissolved water and mechanical impurities in the LRF, unlike aviation fuels.

One of the promising types of rocket fuels are hydrogen fuel cells. The results of the research can be applied in the field of spacecraft operation, as well as refueling infrastructure and cleanliness of rocket fuels. The research results can also be used by chemical experts, specialists in the field of operation of refueling and storage of LRF.

Keywords: *liquid rocket fuel, rocket carrier, refueling object, fuel tank, fuel purity, fuel cell.*

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1. Introduction

It is known that today the issue of economical and fullness of energy using, in particular such energy carriers as oil, gas and coal, is very acute. Oil and oil products are multicomponent media [1, 2], which contain heavy and light fractions. The presence of resins, asphaltenes and paraffins in crude oil determines its ability to change its viscosity when exposed to various factors [2, 3]. Among these factors are heating, the introduction of special additives – inhibitors, exposing to ultrasonic radiation or alternating electromagnetic field, cavitation treatment [4–6].

The world practice of aircraft and missiles operation has accumulated a huge amount of statistical data on the failure of onboard systems due to the increased level of working fluids contamination. Statistics show a decrease in operational reliability due to contamination of working fluids of aircraft fuel systems. For this reason: almost 30 % of all accidents and catastrophes occur; up to 50 % of aircraft engine failures happens; from 20 to 40 % hydraulic failures occur; almost 10 % of fuel system failures happens. Because of this, the service life of pumps and other units is reduced by 6–7 times [3, 4]. According to these data, contamination of liquid fuels and working fluids leads to clogging of injectors and small holes, jamming of spool pairs and fuel-command units. It contributes to accelerated wear of pumps and actuators, to increased leakage through the gaps of movable joints. It is also known that the purity of jet fuels depends not only on the quality of their filtration, but also on the cleanliness of workplaces, cleanliness of detergents and process fluids, cleaning efficiency, flushing efficiency, quality control of cleanliness of working units and pipelines. Substantial part of the contamination consists of impurities left over from the manufacture of the product. They are residues from heat and mechanical treatment, fitting and grinding, residues of abrasive pastes after these operations are finished.

Problems of ensuring the quality of aviation and rocket fuels have been remained open and relevant. High levels of fuel purity guarantee flight safety, guarantee reliability, increase the technical resource of system units. As a result, the costs of achieving and maintaining the required level of purity of fuels and working fluids are fully justified. The issues of systematization and improvement of methods and means of industrial cleaning have been remained relevant also. Problems of industrial purity of liquids are connected with economy of material resources, environmental protection and improvement of sanitary working conditions.

2. The object of research and its technological audit

The object of research is the use of rocket fuels on the example of Ukraine, the state of the art and prospects. Ukraine's joining two international agreements on the reduction and limitation of certain types of armaments has led to a number of government programs emergence and implementation. These are programs for the gradual reduction and elimination of strategic ground-based and air-based weapons, nuclear delivery vehicles and related infrastructure. Reconstruction of areas contaminated by military activity has also begun. It was necessary to neutralize objects that pose an environmental threat (missile weapons, technological equipment, facilities, etc.), as well as components of rocket fuel, during the implementation of these programs.

The ban on the use of highly toxic nitric acid-based rocket fuels has necessitated their replacement with less toxic ones. The lack of production of petroleum-based hydrocarbon rocket fuels in many countries, including Ukraine, exacerbates this problem.

3. The aim and objectives of research

The aim of this research is to form technical requirements for rocket fuels to ensure their purity, safe refueling and use.

To achieve this aim it is necessary to solve the following objectives:

1. Performing a comparative analysis of the main physical, chemical and operational properties of the existing range of the modern rocket fuels brands suitable for use in Ukraine.
2. Forming a classification of liquid rocket fuels based on their component composition and chemical structure.
3. Formulating requirements to energy, kinetic, operational characteristics; ecological and economic properties of liquid rocket fuels (LRF) for development of standards on quality their control during their storage and operation.

4. Research of existing solutions to the problem

Many brands of rocket engines are known. Their technical and operational characteristics determine the ability of the launch vehicle to bring a particular cargo into orbit. The development of rocket engines, with no doubt determines the overall level of astronautics. Liquid rocket engines deliver payloads to the International Space Station (ISS), deliver satellites to Earth orbits, and drive the rocket stages of spacecraft to explore outer space. Solid propellant rocket engines are typically used to deliver weapons in the conditions of the Earth's atmosphere. Therefore, the research will consider using the liquid rocket fuels.

There are different approaches to the classification of liquid rocket fuels: based on the method of application in liquid rocket engines; on the chemical composition of the components; on the principle of their ignition in the combustion chamber; on the main purpose. Liquid rocket fuels are divided into one-component (sometimes called unitary) and two-component fuels according to the method of application in engines.

Single-component rocket fuels are divided into monomolecular and mixed according to their chemical composition. Monomolecular single-component fuels include compounds whose molecules contain both combustible elements and oxygen required for combustion. Such compounds are, for example, esters of nitric acid and various mono-, di- and trihydric alcohols (methyl nitrate CH_3ONO_2, ethyl nitrate $C_2H_5ONO_2$, isopropyl nitrate $C_3H_7ONO_2$, ethylene glycol dinitrate C_2H_4 (ONO_2), etc.); nitroparaffins (nitromethane CH_3NO_2, nitroethane $C_2H_5NO_2$, nitropropane $C_3H_7NO_2$, etc.).

Single-component fuels can also include endothermic compounds that emit large amounts of heat and gaseous products during their decomposition (for example, hydrazine N_2H_4, ethylene oxide C_2H_4O, hydrogen peroxide H_2O_2, etc.).

Two-component liquid rocket fuels, in which each of the components is fed into the combustion chamber separately, consist of fuel and oxidizer.

Rocket oxidizers, according to their chemical nature (the name of the main element), can be divided into the following [7]:

- oxygen based – liquid oxygen O_2 and ozone O_3, hydrogen peroxide H_2O_2;
- nitrogen based – concentrated nitric acid HNO_3, nitrogen oxides N_2O_5, N_2O_4, N_2O_3, NO, N_2O, mixtures of nitric acid (nitric tetraoxide), tetranitromethane $C(NO_2)_4$;
- fluorine based – liquid fluorine F_2, oxygen fluorine compounds, in particular fluorine monoxide OF_2, chlorine trifluoride ClF_3, chlorine pentafluoride $C1F_5$, nitrogen trifluoride NF_3, perchloryfluoride $C1O_3F$, fluoronitrate FNO_3, tetrafluorohydrazine and N_2F_4, etc.;
- chlorine based – liquid chlorine $C1_2$, perchloric acid $HC1O_4$ and chlorine oxides, in particular CI_2O_7.

Rocket fuels by chemical composition are divided into [7]:

- hydrogen – liquid and sludge-like hydrogen H_2;
- hydrocarbon based – petroleum origin type RP1, Jp-5, Jp-6, T-l and synthetic, usually in the form of individual compounds, in particular, with cyclic structure, as well as liquid methane CH_4 and propane C_3H_8. Hydrocarbon fuels can also include alcohols – methanol CH_3OH, ethanol C_2H_5OH, isopropanol C_3H_7OH, furfuryl alcohol $C_5H_6O_2$;
- hydrazine based – hydrazine N_2H_4 and its alkyl derivatives, in particular N-dimethylhydrazine $(CH_3)_2N$-NH_2 (NDMG), monomethylhydrazine CH_3N-NH_2 and phenylhydrazine C_6H_5N-NH_2, Aerosin-50, which is a mixture of hydrazine and NDMG in relation to 1:1, hydrazinazide, etc.;
- amine based – liquid ammonia NH_3, individual amines, for example, aniline $C_6H_5NH_2$, ethylamine – mono-C_2H_5N-NH_2, diethylenetriamine, etc., mixtures of aliphatic and aromatic amines, in particular, a mixture of triethylamine and isomeric xylidines $(CH_3)_2C_6H_5NH_2$ in relation to 1:1, etc.;
- borohydrogen – compounds such as boranes B_nH_{n+4}, for example, decarborane $B_{10}H_{14}$ and diborane B_2H_6, dihydroborane B_nH_{n+6}, for example, pentaborane B_5H_{11}, etc.;

– metal-containing – homogeneous compounds such as triethylaluminum, hydrides (MH_2) and borohydrides $M(BH_4)$ of aluminum, lithium and beryllium (n – valence of the metal) and heterogeneous metallized suspensions of these metals in hydrazine and hydrocarbons.

The classification of liquid rocket fuels, based on their component composition and chemical structure, is presented in Fig. 1. According to their direct purpose, liquid rocket fuels are divided into basic, launch and auxiliary.

The basic fuels are used to burn in the combustion chamber and obtain the required thrust of the engine, launch – to ignite non-self-igniting fuel components in the combustion chamber, auxiliary – to ensure the operation of auxiliary units of liquid rocket engines (LRE) (turbopump, liquid pressure accumulator, etc.) [7].

The research [8] proposes an alternative version of rocket fuel. The paper presents an experimental study of the distillation of hydrogen peroxide to increase the concentration of the solution in order to use it as rocket fuel. Obtaining the concentration required for the rocket engine operating in the wind tunnel was realized using the method of vacuum distillation. The key factors contributing to the desired concentration were evaluated and the results of the experiments were compared with the calculated ones. However, the paper does not show the results of such fuel field tests, but only makes assumptions about its successful use on first-stage missiles.

The research [9] is devoted to the study of possible improvements of combustion properties of multicomponent solid fuels by applying methods of topology optimization to a representative volume element (RVE) of HMX-aluminum fuel. A family of wire-like solutions has been found that provide optimal combustion properties and engine construction. Estimation of combustion productivity showed an improvement in the rate of flame propagation by 52 and 33 % compared to previous designs at the pressure of 20 and 200 atm, respectively. However, in our opinion, this type of fuel is suitable for use in surface-to-air rockets and it is not clear from the description what thrust impulse will provide such fuel and will it be enough to accelerate a spacecraft to the first space speed.

The research [10] investigated the use of asymmetric dimethylhydrazine (UDMH) in Russia. The authors found that not all fuel on board is consumed at launch. Residual fuel tends to flow out of the stages and form aerosol clouds that drift over large areas and pollute the environment. Canada and Greenland are very concerned about this issue. It is because such toxic rocket fuel is still being dumped over their areas. The authors note that this is a violation of several treaties as well as international law.

The research [11] represents a preliminary assessment of the potential impact of UDMH on the environment and human health because of space activities. The theoretical basis includes modeling of QSAR, ADME and PASS, as well as the study of possible dispersion of UDMH in the atmosphere, calculated using the OML-Multi model. The authors identified a possible impact on the environment and human health. It was also concluded that UDMH, which is dumped on the ground along with the first stage of the rocket carrier, poses a significant threat to both the environment and human health. It is possible to fully agree with the results of this research.

The research [12] investigated the possible effect of 1,1-dimethylhydrazine (heptyl) and its transformation products on human health. The author used both ADME models and acute toxicity models specific to organs with adverse hematological effects, cardiovascular and gastrointestinal systems, kidneys, liver and lungs, as well as a model that predicts the biological activity of the compounds. The research predicts that all of the compounds tested are readily bioavailable orally and that significant amounts of the compounds can freely penetrate into systemic blood circulation. In addition, it is assumed that several compounds have a high potential of carcinogenicity, mutagenicity, teratogenicity and/or embryotoxicity. The effects on living organisms modeled by the research have already been confirmed experimentally by other researches.

The research [13] is devoted to modeling the processes of soil contamination by toxic heptyl rocket fuel (asymmetric dimethylhydrazine, UDMH) and the product of its conversion by N-nitrosodimethylamine (NDMA). Laboratory conducted experiments show that the reaction of UDMH conversion to NDMA is reversible in gray-brown soil (uncontaminated soil samples were taken from the area of the Baikonur Cosmodrome) and depends on the concentration of interacting substances. NDMA is transmitted by soil to the stems and leaves of wild plants. The ability of leaves and stems to accumulate NDMA depends on plant species.

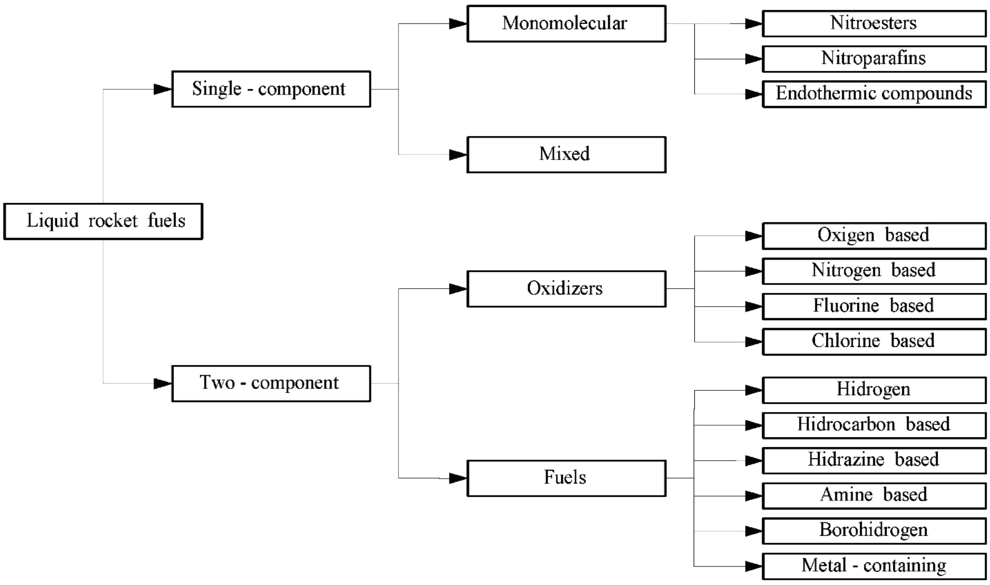

Fig. 1. Classification of liquid rocket fuels

The article [14] presents the results of the study of heptyl formation and its accumulation in wild plants growing in soils contaminated with rocket fuel, at the sites of accidental falls of Proton-M launch vehicles in Central Kazakhstan. It has been experimentally proven that certain concentrations of heptyl in gray-brown sandy soils are not phytotoxic to *Agropyron pectiniformee* (1–5 mg/kg) and *Artemisia dracunculus L.* (1–25 mg/kg). However, it has ability to cause anatomical morphological changes in the roots and leaves. The detected symptoms increase with increasing dose of soil contamination with heptyl above 25 mg/kg.

As can be seen from the analysis of the researches, one of the major types of rocket fuel is heptyl and its derivatives, although the question of its toxicity remains open. That is why many researches [14–16] are devoted to the study of its impact on soils, water, flora, fauna and humans.

Very few scientific researches have been devoted to finding and researching alternative rocket fuels. It is due to the specifics of the use of rocket fuels and the high requirements for them. This issue is almost not considered at all in Ukraine, given that the country has never produced such fuels. However, Ukrainian-made rockets accounted for almost 20 % of world use during the launch of high-tonnage spacecraft by Russia, USA, France and Canada in 2020.

Thus, the results of the analysis allow concluding that the world has very high requirements for rocket fuels and for their quality. However, the problems of refueling and purity of rocket fuels have been remaining open and relevant. The question of the nomenclature of brands of modern rocket fuels suitable for use also remains open for Ukraine, as the country does not produce its own rocket fuels.

5. Methods of research

A comprehensive approach to fuel quality assessment, analysis of world experience, synthesis of results and retrospectives, historical-evolutionary and logical approach is used.

Analysis of research and publications shows that liquid and solid rocket fuel had been used until recently to refuel rocket carriers in Ukraine. As it is known, liquid fuels due to their physicochemical properties pose a greater threat. The release of them into the environment was more massive, and the decomposition and migration was more intense. The most environmentally hazardous are hydrazine rocket fuel – UDMH and heptyl. UDMH is extremely dangerous due to its high toxicity, so it is classified by the World Health Organization (WHO) as a first-class hazard substance [15].

Recent experimental studies of the diffusion, sorption, desorption, filtration, and decomposition of UDMHs in different types of soils selected from areas of fuel straits have shown that heptyl is oxidized by air in the environment with the formation and accumulation of a number of stable transformation products. The researches [15–17] found that dimethylamine, methylhydrazine, trimethylhydrazine, tetramethyltetrazene, formaldehyde, nitrosodimethylamine, methylenedimethyl-hydrazine and other products are formed in soils contaminated with UDMH.

The nature of UDMH migration in landscapes is determined by its high evaporation, air oxidation, solubility in water, high sorption capacity [17]. The solubility of UDMH in water allows it to penetrate the soil along with precipitation to easily reach unprotected aquifers and then enter water bodies far from the outflow sites [15, 16]. Heptyl has a high resistance in the soil (stability more than 12 months) and plants (storage for more than 12 months), migrates well in the soil profile (from 60 to 200 cm and more). The research [15] established a clear dependence of UDMH uptake by soil on the content of organic matter and its strong connection with the organomineral complex of the soil.

Amin fuel TG-02 (Tonka-250, samin) – rocket fuel, which is a mixture of technical isomeric xylidines and technical triethylamine [15]. Samin is a poisonous and carcinogenic substance, which according to its toxicological characteristics belongs to the third class of hazard.

Liquid oxidizers of rocket fuel based on nitric acid – NT and AK-27И – pose a significant danger. NT (nitrogen tetraoxide, amyl) – oxidizer of rocket fuel. It is a derivative of highly toxic concentrated nitric acid, which is classified as hazard class 1 [2, 3, 7]. AK-27И (melange) is a fuel oxidizer, which is a solution of nitric tetraoxide (27 % by weight) in nitric acid (73 %) with the addition of a corrosion inhibitor – crystalline iodine. Melange poses a significant environmental hazard because it is a highly toxic substance [15, 16]. Nitrogen oxidants, getting into the soil, interact with the alkalis present in the soil and form mixtures of nitric salts and nitric acids – nitrates and nitrites, which are stable compounds.

As a result, it should be noted that aviation kerosene (kerosene) remains less harmful to the environment from an ecological point of view.

For reference [7] – aviation kerosene is used for missile technology produced in the Russian Federation (RF) for subsonic aircraft according to GOST 10227-2013 and for supersonic aircraft according to GOST 12308-013. There are 5 brands of fuel for subsonic aviation (TS-1, T-1, T-1C, T-2 and RT), for supersonic – 2 (T-6 and T-8B). Mass fuels are currently TS-1 fuels (premium and first grades) and RT fuels, premium grade, which is also currently produced in Ukraine at the Kremenchug Refinery (Refinery). Aviation kerosene T-1 has been the main fuel for the space rockets for many years. Kerosene T-1 was chosen as the fuel for intercontinental ballistic missiles (ICBMs) R-7, based on which space-based missiles were created: rocket carriers (RC) «Sputnik» (the first three Soviet artificial satellites of the Earth). RC «Vostok» (First manned flight), RC «Lightning» (first communication satellite), RC «Soyuz» (manned flights and satellites for various purposes). It is used mainly for LRE PD-107 (first stage, «side engines») and PD-108 (second stage, central unit), which, taking into account repeated upgrades and modifications, have been in serial production for almost 60 years. The choice of aviation kerosene T-1 as the main fuel for liquid fuel engines (LFE) ICBM P-7 and all subsequent space rockets was determined by the cheapness and availability of T-1, as well as low toxicity and simplicity of ground infrastructure.

Petroleum-based jet fuels T-1, T-6, T-8B are also well suited for Ukrainian-made space technology, but the problem is that they are not produced in Ukraine, and their purchase in Russia is currently not possible for a number of reasons. Therefore, Ukraine needs either to start producing its own fuels of these brands, or to buy analogues in other countries. At the beginning of 2020, negotiations were held with the United States and Canada on the purchase of RP-1 rocket fuel at the Pivdenne Design Bureau. Therefore, a comparative analysis of existing rocket fuels suitable for use in Ukraine, analysis of technical requirements for rocket fuels and analysis of the problem of refueling and purity of rocket fuels will be done in this paper.

Long-term experience in the use of jet fuels shows that they must meet energy requirements, requirements for the kinetic properties, operational properties requirements, environmental and economic requirements [17–19].

Requirements for energy characteristics of LRF:

1. LRF must have high value of the ideal specific impulse of thrust or mass heat of combustion value. The higher the mass heat of combustion value of the fuel, the higher is the flow rate of combustion products from the nozzle, and hence the higher is the specific thrust.
2. LRF must have high fuel density. The density of the fuel, along with the specific impulse, has a major impact on the most important characteristic of the aircraft – its final speed, i. e. the speed at the end of the active part of the flight path at the end of the engines operation.
3. LRF must have high value of gas constant of combustion products R_{comb}. It provides more specific gas formation during combustion process.
4. LRF must have low value of the adiabatic index of combustion products.
5. LRF must have acceptable level of combustion products temperature in the combustion chamber T_{comb}.

Requirements for kinetic properties of fuel:

1. LRF must have the possibility of spontaneous combustion of fuel in the combustion chamber in case of contact of its components in liquid form. Fulfilling this requirement significantly increases the reliability of the engine and simplifies its design, because there is no need for a special fuel ignition system.
2. LRF must have low ignition temperature of fuel components. It helps to increase the reliability of the LFE launch.
3. LRF must have low ignition delay.
4. LRF must have high rate of fuel combustion, i. e. high rate of chemical reactions.

Performance requirements. Requirements for fuel performance can be divided into two groups:

1. Fuel requirements as a combustion chamber cooler.
2. Requirements to maintenance and operation of the engine.

The requirements of the first group are designed to provide reliable cooling of the engine chamber:

1.1. Coolant must have high specific heat capacity. At high specific heat capacity, the unit of mass of the cooled component will absorb more heat.

1.2. Coolant must have satisfactory thermal conductivity. A liquid with high thermal conductivity is able to transmit and distribute large heat flows.

1.3. Coolant must have high boiling point.

1.4. Coolant must have significant chemical resistance in case of contact with the fire wall of the chamber heated to a temperature of 570–970 K. On the walls of the flowing part of the external regenerative cooling system of the chamber should not be formed carbon deposits or coke, which impairs heat dissipation from the wall to the colder body.

1.5. Coolant must have low viscosity. The high viscosity of the cooling component increases the hydraulic resistance of the cooling path of the chamber. This requires increasing the power of fuel pumps.

Requirements of the second group related to engine maintenance and operation:

2.1. Fuel must have stability at long storage. Fuel components should not evaporate, stratify, change their structure and chemical composition, and emit sediments during storage.

2.2. Fuel must have minimum corrosion activity in relation to the materials of the fuel supply system.

2.3. Fuel must have low freezing point. It is desirable that the freezing temperature was not higher than −40 °C.

2.4. Fuel must have high boiling point. The boiling point should not be below +50 °C.

Compliance with the last two requirements simplifies the maintenance and use of LFE throughout the operating range of ambient temperatures.

2.5. Fuel must have high explosion and fire safety.

Requirements for environmental and economic properties. These requirements ensure the safety of engines and their competitiveness in the global market:

1. Fuel must have low cost.
2. Fuel must have no deficiency.
3. There must be provision of raw materials. Fuel components should be manufactured using domestic raw materials and domestic plants, if possible.
4. It must be ease to manufacture the fuel.
5. There must be the possibility of using fuel, its components and their derivatives in the national economy.
6. Fuel components and combustion products shall not be toxic.
7. The production and operation of engines and fuels must be environmentally friendly.

It should also be noted that there is no fuel, which meet all these requirements.

Therefore, when selecting fuel components, they have to look for compromises and find optimal solutions. In the case of the formation of the objective function, first of all attention should be payed to the implementation of the basic requirements.

6. Research results

There is shown typical properties of jet fuels produced in Ukraine (PT and TC-1), jet fuels used for rocket technology and produced in Russia (T-1 and T-6), rocket fuels produced in the USA and Canada and recommended for use in Ukraine (RP-1 and JR-5) in the Table 1.

As can be seen from Table 1, jet fuels are very similar in basic properties. As for rocket fuels, JP-5 kerosene is close in cooling properties to T-1 kerosene at low temperatures, but with a tendency to exceed the cooling properties by 10–20 %.

As for kerosene RP-1, it shows better properties than JP-5 at low temperatures. Given the monotony of the functions of density, heat capacity, thermal conductivity and viscosity, this trend is likely to continue at high temperatures $T \geq 200$ °C. Comparative analysis shows that RP-1 fuel is in most respects an analogue of T-6 jet fuel, and therefore can be used for rocket carriers made in Ukraine. The only indicators by which RP-1 jet fuel loses to T-1 and T-6 fuels are the crystallization start temperature and the allowable sulfur content. However, RP-1 rocket fuel has a higher combustion heat value and much lower allowable concentration of actual resins, which is very important for the operation of rocket engines (RE).

Table 1

Comparative characteristics of jet fuels suitable for rocket engines from different countries

Index	PT DSTU 320.00149943.007 (Ukraine)	TC-1 DSTU 320.00149943.011 (Ukraine)	Rocket fuel JP-5 (USA, Canada)	Rocket fuel RP-1 MIL-DTL-25576E (USA, Canada)	T-1 GOST 10227-2013 (Russia)	T-6 GOST 12308-2013 (Russia)
Fractional composition:						
– boiling point (start):				must be determined 185–210	150	195
10 %, °C	175	175	199		175	220
50 %, °C	225	225	220	–	225	255
90 %, °C	270	270	246	–	270	290
– boiling point (end), °C	–	–	–	max 274	282	315
– remainder, %	–	–	–	max 1.5	–	–
– losses during evaporation, % mass	–	–	–	max 1.5	–	–
Flash point, °C	min 30	min 28	64	min 60	min 30	min 62
Crystallization start temperature, °C	–55 max	–55 max	–45	–51 max	–60 max	–60 max
Kinematic viscosity, mm^2/sec at the temperature of minus 40 °C at the temperature of minus 34 °C	max 16	max 16	13.8	max 16.5	max 16	max 60
Combustion heat value, kJ/kg	min 43100	min 43120	48.5	min 43031	min 42900	min 42900
The concentration of actual resins, mg per 100 cm^3 of fuel, no more	max 4	max 5	–	max 1	max 6	max 4
Mass fraction of total sulfur, mg/kg	max 0.1	0.25	30	max 30	max 0.1	max 0.001
Mass fraction of mercaptan sulfur, mg/kg	0.001	0.003	0.003	max 3	–	max 0.005
Mass fraction of aromatic hydrocarbons, mg/kg	max 22	max 22	5	max 5	max 18	max 8
The content of mechanical impurities, mg/l	0.0003	0.0003	<1	max 1	absent	absent
Corrosion on a copper plate	max 1	max 1	max 1	max 1	max 1	max 1
Density, 60/16 °C	–	–	–	0.799–0.815	–	–
Density at 20 °C, g/sm^3	0.775	0.778	0.824	–	0.800	0.840

It is known that the operational safety of aircraft with gas turbine engines (GTE) and RE largely depends on clear organization of refueling them with conditioned fuels. The use of fuel for gas turbine engines in civil aviation of Ukraine and the technology of refueling aircraft are clearly regulated by instructions and guidelines, non-compliance with which often leads to loss of fuel quality and violation of the flight schedule creates preconditions for flight events [20, 21].

Fuels for GTE and RE may change their properties during storage, transportation and refueling. Non-conditioned fuels negatively affect the operation of aircraft fuel systems and missiles. The automatic control of refueling in fuel systems can fail, and premature clogging of filters can occur.

The fuel control equipment of GTE is especially sensitive to contamination [22, 23]. There is pollution of two types in each working liquid. «Inherited» pollution, which ended up in the fuel from raw materials in the process of production and «acquired» pollution – those that got to liquid because of wear of friction pairs of units, contact with environment or appeared because of physicochemical changes. Crude oil, which almost all traditional fuels are produced from, contains undesirable components, such as unsaturated hydrocarbons, asphalt-resinous substances, ash elements, naphthenic acids, nitrogen and sulfur compounds, solid paraffins, ceresites, water, etc. [22]. Timely cleaning of working fluids of fuel systems increases the reliability and durability of equipment. While using non-conditioned fuels jamming of precision pairs in the pumps-regulators of jet engines can occur. It causes instability of engine start, fluctuations in speed or self-shutdown of the engine. According to research [23], the durability of the fuel system and equipment can be increased by 2–3 times only by cleaning and improving the purity of the working fluids. Therefore, the issues of improving the purity of fuels for GTE are particularly promising.

It is known that contaminants enter the technical fluid:

- during system maintenance; in case of poor installation of units, flexible hoses and pipelines;
- through open connecting nodes;
- due to contamination of tools, refueling facilities, clothing of service personnel;
- in case of refueling in contaminated tanks;
- in case of pumping by poorly flushed pipelines.

In the warehouses of aviation fuel supply services of airports, the contaminants enter the fuel:

- in the form of corrosion products of tanks and technological equipment;
- due to wear of pumping means, destruction and leaching of gaskets and sealing materials:
- in the form of dust and moisture entering the tanks during large and small «breaths» of the tanks;
- when filling refueling facilities.

According to ICAO Directive Doc 9977 [24], clean and dehydrated fuel is a guarantee of aircraft safety. The following requirements for water content and mechanical impurities are set for aviation fuels:

- according to sources [18, 19] – complete absence of free water, and the presence of mechanical impurities not exceeding 5 μm;
- according to the source [24] – complete absence of free water, and the presence of mechanical impurities not exceeding 4 μm.

As can be seen from the regulations, these requirements apply to aviation jet fuels used in Ukraine and around the world. However, there is no clear policy information on the water content and mechanical impurities in Ukraine. During the preparation of the LRF for refueling, there is a strict adherence to the standards for the fuels themselves.

Thus, the following requirements for water content and mechanical impurities are set for the considered rocket fuels:

- according to the source [20] – for rocket fuels based on hydrazine allowable solid particles – not more than 15 %;
- according to the source [24] – for liquid rocket fuels the mass fraction of water should not exceed 0.17 %;
- according to the source [25] – for US rocket fuels, the mass fraction of water should not exceed 0.15 %.

Processes of preparation of hydrocarbon fuels intended for refueling of fuel tanks of rockets, rocket and booster units are reduced to:

- purification of fuels from solid particles;
- dehydration (removal of free (emulsion and dissolved) water);
- removal of dissolved gases (degassing);
- cooling or heating to the required temperature before refueling operations at technical or launch complexes of spaceports. Preparation of LRF is done with consecutive carrying out of such operations: purification at reception; dehydration; decontamination; temperature preparation; purification before delivery to the consumer.

According to the considered standards [20, 21, 25] rocket fuels should be cleaned to 5–20 μm with degassing. It must be done taking into account quantity of the fuel, control of its quality during reception, and also free water removing to the content no more than 0.0015 % by weight. The content of dissolved water in LRF should not exceed 0.0001–0.0004 % by weight, which is due to the need to cool the fuel to temperatures (–30)–(–40) °C before refueling the fuel tanks of rockets.

An important quality indicator of the hydrocarbon fuel cooled to sub-zero temperatures is ensuring its pumpability through the filters of refueling and onboard fuel systems. It also requires reducing the content of free and dissolved water in the fuel to values not exceeding 0.0004 % by weight before refueling in the fuel tanks of rockets. It is because the main reason of deterioration of pumping ability of fuel is clogging of filters by ice crystals.

In general, the required properties of hydrocarbon fuels with respect to water content can be provided in several steps – from the production of fuel at refineries to its dehydration during preparation for refueling at ground complexes. During the production of rocket fuels, they are not dehydrated. This process is not a stage of fuel production, and the content of water dissolved in it is not regulated. Therefore, the task of fuel dehydration should be solved exclusively by means of ground infrastructure of spaceports.

Purification of fuels from contaminants and water has been carried out using such common methods as settling, filtration, centrifugation and chemical treatment. According to the civil aviation standards of Ukraine, purification of fuels for GTE at the airports and on the board has been carried out by a filtration method. This method is based on the passage of fuel through a porous membrane, which retains dirt and water droplets. Different types of fabrics, paper, mesh, ceramics, metal ceramics, etc. are used as filter barriers.

Airport and on-board filters for fuel purification are devices with filter elements of disk, spiral, cylindrical and other types. Filters for fuel purification from pollution and emulsion water are being developed in the United States (Millipor Filter Corp., Fram Corp.), the United Kingdom (Millipor Filter Corp., Stream Line Filter Ltd.) and other countries [22].

However, the problem with purifying rocket fuels with filter elements is that they are fed into rocket tanks only at subzero temperatures, unlike aviation fuels. Filter materials that can dehydrate LRF at subzero temperatures are usually very expensive and have a maximum operating resource only to 500 thousand liters.

There are other known alternative methods of working fluids purification. Their principle of operation is based on the effect of interaction of contaminant particles with the force field: gravitational, centrifugal, magnetic, electric and fields of ultrasonic vibration forces.

These circumstances require the search, analysis and justification of rational technologies and modes of cooling and preparation of rocket fuels, control of water content by means of technical complexes of spaceports. These are the tasks of research, educational and scientific laboratories «Alternative motor fuels» and «Technological processes in aviation fuel supply» of the Faculty of Environmental Safety, Engineering and Technology of the National Aviation University (Kyiv, Ukraine).

7. SWOT-analysis of research results

Strengths. The strengths include the identified possibility of using American liquid rocket fuel RP-1 for Ukrainian-made rocket carriers, as in most respects it is an analogue of T-1 and T-6 jet fuel.

Weaknesses. Weaknesses include:

– unresolved problem in the development of regulations on rocket fuels quality control;

– lack of clear regulatory standards for the process of refueling missiles at low temperatures;

– lack of regulations and other standards for the content of free and dissolved water and mechanical impurities in fuels.

Opportunities. The formed requirements to energy, kinetic, operational characteristics, ecological and economic properties of liquid rocket fuels are capable:

– to accelerate the development of regulations on quality control of rocket fuels during storage and operation;

– to ensure the safety of engines and their competitiveness in the world market.

Threats. The negative effects of the rocket fuels application on the environment has been studied insufficiently. Experience shows that traditional rocket fuels, which can potentially be used for Ukrainian rocket launchers, pose significant threats to the environment. Reducing such threats requires further research to improve the physicochemical properties of the fuels used.

8. Conclusions

1. A comparative analysis showed that RP-1 fuel is in most respects analogous to T-1 and T-6 jet fuel, and therefore can be used for modern rocket carriers. The only indicators by which RP-1 jet fuel loses to T-1 and T-6 fuels are the crystallization start temperature and the allowable sulfur content. However, RP-1 fuel has a higher heat of combustion value and a much lower allowable concentration of actual resins, which is very important for the RE operation.

2. The classification of liquid rocket fuels based on their component composition and chemical structure is formed. The classification allows identifying the nomenclature of modern fuels brands that are the most suitable for applications in modern rocketry. It will make possible to do economically and technologically equivalent substitutions of more toxic fuels with less toxic ones. It can result in improving the environmental conditions at missile launch areas.

3. Requirements to operational characteristics, ecological and economic properties of LRF are formed. These requirements will allow the development of regulations governing the quality control of fuels during storage, transportation, and application.

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