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R. V. Mykhalchyshyn, M. S. Brezgin, D. A. Lomskoi

Yangel Yuzhnoye State Design Office, Dnipro, Ukraine

METHANE, KEROSENE, AND HYDROGEN COMPARISON AS A ROCKET FUEL FOR LAUNCH VEHICLE PHSS DEVELOPMENT

Liquid oxygen and methane are often regarded as new promising propellant components. The topic of this paper is a comparative analysis of methane, kerosene, and hydrogen as a rocket fuel in combination with liquid oxygen. Advantages and disadvantages of each component are shown. Pneumohydraulic system has been developed with optimized parameters of subsystems.

Keywords: *propellant components, tank, gas bottle, chilldown, pressurization, pneumohydraulic supply system, payload.*

INTRODUCTION

Recently, the pair of liquid oxygen and methane has been considered as a new «clean» fuel alternative for space missions. Methane is a pure hydrocarbon as kerosene and a cryogenic fuel compared to hydrogen. Methane can be easily extracted from natural gas (LNG). It is non-toxic and non-corrosive. Liquid rocket engines (LRE) burning liquid oxygen/methane have never been used on launch vehicles (LV), but many studies and some tests of their application in Russia [5], Japan [3], USA, Korea [8], and Europe [2] were issued.

The main objective of our study is to analyze an effect of methane application on the PHSS (pneumohydraulic supply system) characteristics, to determine the design features of the system and its main parameters.

Despite the huge amount of information on the development of engines powered by these components, at present there is no information on the appearance of the PHSS of launch vehicles.

From the published materials [2, 3, 5, 8] the following advantages of methane application are known:

- Increase of the specific impulse of thrust by ~8 % with moderate parameters (p_k = 16...19 MPa) as compared to oxygen-kerosene LRE with high parameters (p_k up to 26 MPa);
- Simplicity of production and low cost;
- Ecological cleanliness (toxicity of combustion products is 14.5 % lower);
- The chilldown capacity of methane is 2.5 times higher as compare with kerosene;
- Increasing LRE reliability by using reconstruction gas generator;
- Possibility of using control blocks of LRE on gaseous components;
- Gasification and complete removal of fuel residues in tanks and feedlines after landing of the stage or discharge;
- Reduction of the heat resistance requirements of LRE structural materials (gas temperature before the turbine up to 600 K), etc.

The main disadvantages of methane usually include its low density (46 % lower than kerosene).

During the research, a number of acts were undertaken to overcome this negative effect [6].

COMPARATIVE ANALYSIS OF METHANE, KEROSENE, AND HYDROGEN

Table 1 provides a comparison of the main characteristics of methane, kerosene, and hydrogen, as a fuel for LRE. Based on such parameters as the density of the liquid and the specific heat of combustion, it follows that in order to have 100 MJ of energy on board, a hydrogen tank of 14 liters, or only 4 liters of methane, or 2.7 liters of kerosene should be required. But from the point of view of unification, the cryogenicity of methane is more of an advantage than a disadvantage, because it still requires an infrastructure for liquid oxygen, which boils at lower temperatures than methane. Moreover, hydrogen requires temperatures four times lower than oxygen (on an absolute scale).

If we consider the oxidizer, for the same 100 MJ of energy for the combustion of hydrogen, 6.6 kg (5.8 l) of oxygen will be needed. At the burning of methane 7.25 kg — 6.35 l correspondingly, the volume of tanks in the launch vehicle at «methane + oxygen» is half than of «hydrogen + oxygen» with equal energy intensity. With equal impulses, the difference will be somewhat less, but still in favor of methane. This is if we do not take into account the complexity of the tank's design needed for hydrogen [4].

STRUCTURAL COMPARISON OF METHANE AND KEROSENE

As the basis of the first stage propellant system, we consider the design system developed at the Yuzhnoye State Design Office for comparison. Its efficiency was confirmed by numerous successful launches. In this case, the volume of the oxidizer tank corresponds to the prototype, and the flow rate is close in value. Based on the density and the optimal ratio of propellant components, an increase in the volume of the fuel tank will be 37 %. At the same time, the «dry» mass of the tank will increase by 18 %. But, close temperature regimes of the propellant components make it possible to use an intermediate bottom, thereby saving almost 1400 kg on the mass of the upper bottom of the fuel tank and the walls of the inter-tank compartment.

Fig. 1 shows the redistribution of the weight characteristics of the LV propellant systems in comparison with the «standard» design. As follows from Fig. 1, the use of methane as a fuel reduces the weight of the tank construction by ~11 %, due to the design of the propellant compartment with an intermediate bottom.

Taking into account that methane is a cryogenic liquid, in order to exclude the geyser effect, it is necessary to provide chilldown of the fuel path before launch, for example, using the circulation system.

Table 1. **Main characteristics of the fuel for LRE**

Parameter, dimension	Kerosene $CH_{1.952}$	Hydrogen H_2	Methane CH_4
Boiling point, K	450—547	23	112
Freezing point, K	224	14	91
Density, for 15 °C, kg/m^3	809	0.09	0.72
Liquid density, kg/m^3	—	70	422.5
Critical temperature, K	662	33	190
Critical pressure, Pa	2 171 848	1 317 000	4 599 200
Specific heat, J/(kg · K)	2 093	14 300	3 480
Service properties	Long-term storage	Cryogenic	Cryogenic
Molecular weight, g/mole	172	2	16
Specific heat of the burning, MJ/kg	55	120	43
Split	2.8	6	3.5

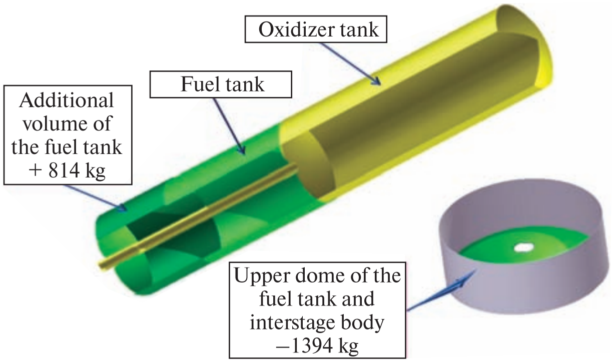

Fig. 1. Changes in the design of the propellant system

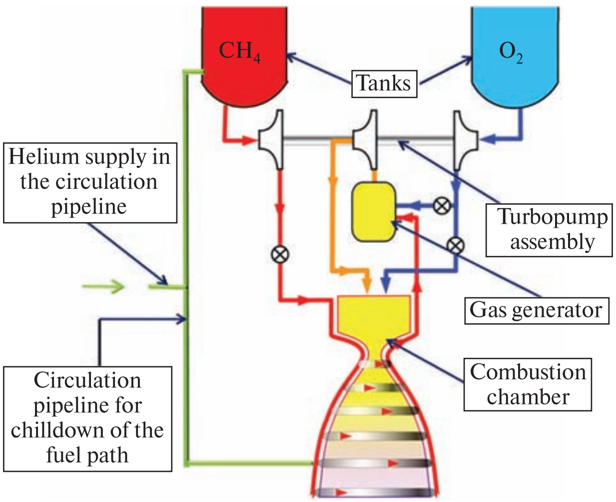

Fig. 2. Chilldown system for fuel path

A chilldown system by circulation method is planned to ensure the required temperature of liquid methane in the engine's inlet (Fig. 2). The system represents a pipeline that connects the after-pump cavity of the engine with the tank and through which the overheated methane is discharged into

Table 2. **Physical and chemical properties of liquid methane and liquid oxygen**

Property, dimension	Liquid oxygen	Liquid methane
Boiling temperature, °C	–183	–162
Melting temperature, °C	–219	–184
Density for normal temperature and pressure, kg/m^3	1140	420
Heat capacity, J/(kg · K)	1709.8	3399

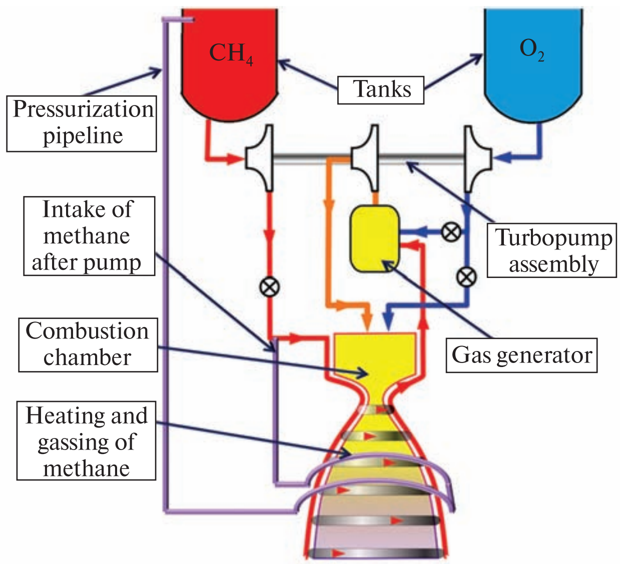

Fig. 3. Principal scheme of the fuel tank pressurization system

the tank. Such a system is effectively applied to maintain the temperature of liquid oxygen in the oxidizer path, so the calculation was performed to assess its performance on methane. Table 2 compares the physicochemical properties of liquid methane and liquid oxygen.

CHILLDOWN SYSTEM OF THE FUEL MAIN ENGINE PATH

Chilldown system of the fuel main engine path is given in Fig. 2.

We performed calculations by the method proposed in [9]

$$\dot{G} = \frac{\rho_{cl} F_{cl}}{\sqrt{\xi + 1}} \sqrt{2gh \frac{\rho_{fl} - \rho_{cl}}{\rho_{cl}}}, \qquad (1)$$

where ξ — total coefficient of hydraulic losses in the circulation circuit, h — height of the circulation pipeline, F_{cl} — cross-sectional area of the circula-

Table 3. **The main characteristics of the methane path chilldown system**

Parameter, dimension	Value
Weight of the construction of the chilldown system, kg	22
Helium flow rate for the «gas-lift», g/s	1
Provided temperature at the engine inlet, K	111.5

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Table 4. **The main characteristics of pressurization systems for oxidizer and fuel tanks**

Tank	Pressurization type	Pressurization gas	Gas constant, J/(kg · K)	Pressurization gas mass, kg	Structure mass of the PS, kg	PS total mass, kg
Oxidizer	Gas-balloon, «cold» pressurization	Helium	212	143	13 bottles mass – 603	746
	Gas-balloon, «hot» pressurization	Helium	212	86	8 bottles mass – 392	**478**
	Pressurization by oxygen	Oxygen	26.5	686	34	720
Fuel	Gas-balloon, «cold» pressurization	Helium	212	104	9 bottles mass – 423	527
	Gas-balloon, «hot» pressurization	Helium	212	68	6 bottles mass – 302	370
	Pressurization by methane	Methane	52	277	32	**309**

tion pipe, ρ_{cl} — averaged over the height value of the component density in the circulation pipeline, ρ_{fl} — averaged over the height value of the component density in the flow line.

In order to understand how the flow rate of the circulating liquid methane and the liquid oxygen are correlated for the same circulation circuit under the same environmental conditions, a relation was derived (in the indices lox is liquid oxygen, and lm is liquid methane):

$$\frac{\dot{G}_{lox}}{\dot{G}_{lm}} = \sqrt{\frac{\rho_{lox\_cl} \cdot (\rho_{lox\_fl} - \rho_{lox\_cl})}{\rho_{lm\_cl} \cdot (\rho_{lox\_fl} - \rho_{lm\_cl})}}. \qquad (2)$$

From this ratio, it was found that under the same conditions in the same circuit the flow rate of the liquid methane would be about 3 times less than for the liquid oxygen. An optimal chilldown system for the methane path was designed taking into account this feature. Its main characteristics are given in Table 3. With a minimum weight of the structure, the proposed chilldown system is sufficiently reliable and provides the necessary thermal modes of the fuel and the engine construction.

PRESSURIZATION SYSTEM CHOICE FOR OXIDIZER AND FUEL TANKS

An important aspect of the design of launch vehicles is the selection of optimal pressurization systems for tanks. One of the main criteria in this alternative is the minimum weight of the system.

Table 5. **Analysis of the impact of the changes presented on the payload mass**

Features	Stage mass changing, kg	Payload mass changing, kg
Chilldown system of fuel path	+32	–2
Fuel tank volume increasing	+814	–50
Combination of the lower bottom of the oxidizer tank and the bottom of the fuel tank	–1 394	+88
Propellant components mass decreasing	–19 802	–396
Tank pressurization by gasify methane	–218	+14
Specific impulse increasing	+23 c	+920
Total mass changing	–20 500	+574

For the choice of the optimum version of the pressurization systems, three types of analysis are performed: cold and hot gas-balloon, as well as tank pressurization with propellant vapors. Calculation of the main characteristics was conducted in accordance with the proven methodology [1].

As can be seen from Table 4, the gas-balloon «hot» pressurization system is optimal for the oxidizer tank, but for the fuel tank, the pressurization by methane vapors is more effective, since the methane gas constant is 52 J/(kg · K). In fact, it reflects the energy efficiency of gas as a working pressurizing body. For the oxidizer tank, the oxygen pressurization is not effective, since the necessary oxygen supply exceeds the weight of the bottles of the «hot» pressurization system, while the «hot» pressurization system is generally lighter than «cold» by ~268 kg.

Figure 3 shows a principal scheme of a rational fuel tank pressurization system. The methane intake is being done after the engine pump. Then it is gasified on the engine chamber and fed into the free gas volume of the tank.

As a result, based on the proven methodology [7], an assessment of the effect of the above changes in the PHSS design on the LV energy-mass characteristics was made and presented in Table 5.

CONCLUSIONS

We have compared methane, kerosene, and hydrogen as combustible for carrier rockets. As a result, we have found that hydrogen requires larger dimensions of LV stages. Due to restrictions on rail transportation, the design of the first stage on hydrogen is not appropriate for the considered LV.

The analysis of changes in the PHSS design resulted from replacement of kerosene with methane with subsequent effect on the energy mass characteristics of the stage and the launch vehicle as a whole showed that for the considered configuration the launch mass of the first stage will decrease by 14 %, while the LV will be able to launch the payload by approximately a half a ton more.

Thus, in the course of complex studies, the results are as follows:

- An effective fuel path chilldown system with the use of the «gas-lift» function is proposed.
- The volume of the fuel tank is increased by reducing the «dry» weight of the structure due to the use of an intermediate bottom of the optimal construction.
- The most rational variants of the oxidizer and fuel tank pressurization systems have been analyzed and selected.
- The effect of methane use on the PHSS characteristics is analyzed, the design features of the system and its main parameters are determined.

In general, the modification of the PHSS for the integration of engines burning the components «methane + oxygen» with a reduction in stage mass by 8 % and an increase in stage height by 11 % leads to an increase in the payload mass by ~10 %.

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Р. В. Михальчишин, М. С. Брезгин, Д. А. Ломський

Державне підприємство «Конструкторське бюро «Південне» ім. М. К. Янгеля», Дніпро, Україна

ПОРІВНЯННЯ МЕТАНУ, ГАСУ ТА ВОДНЮ ЯК ПАЛЬНИХ ПРИ РОЗРОБЦІ ПНЕВМОГІДРАВЛІЧНОЇ СИСТЕМИ ПОДАЧІ ПАЛЬНОГО ДО РАКЕТИ-НОСІЯ

Представлено порівняльний аналіз характеристик метану, гасу та водню як пальних у парі з киснем. Запропоновано систему захолоджування тракту пального, визначено оптимальні системи наддуву баків окиснювача та пального для першого ступеня ракети-носія при використанні метану. На прикладі першого ступеня розробки КБ «Південне» розглянуто конструктивні особливості баків при використанні пар «кисень-метан» та «кисень-гас», показано вплив конструктивних особливостей на масу ступеня та корисного вантажу.

Ключові слова: компоненти палива, властивості, бак, балон наддуву, маса, захолоджування, наддув, корисний вантаж.

Р. В. Михальчишин, М. С. Брезгин, Д. А. Ломской

Государственное предприятие «Конструкторское бюро «Южное» им. М. К. Янгеля», Днипро, Украина

СРАВНЕНИЕ МЕТАНА, КЕРОСИНА И ВОДОРОДА КАК ГОРЮЧИХ ПРИ РАЗРАБОТКЕ ПНЕВМОГИДРАВЛИЧЕСКОЙ СИСТЕМЫ ПОДАЧИ ГОРЮЧЕГО К РАКЕТЕ-НОСИТЕЛЮ

Представлен сравнительный анализ характеристик метана, керосина и водорода как горючих в паре с кислородом. Предложена система захолаживания тракта горючего, определены оптимальные системы наддува баков окислителя и горючего для ступеней ракеты-носителя при использовании метана. На примере первой ступени разработки КБЮ рассмотрены конструктивные особенности баков при использовании пар «кислород-метан» и «кислород-керосин», показано влияние конструктивных особенностей на массу ступени и полезного груза.

***Ключевые слова*:** компоненты топлива, свойства, бак, баллон наддува, масса, захолаживание, наддув, пневмогидравлическая система подачи, полезный груз.