Gas Fuels for Engines of Internal Combustion with Spark Ignition

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Abstract: The article provides information about gas fuels currently used in internal combustion engines, their types and composition. The analysis of the fuels used in these engines, as well as the types of fuels that meet today's environmental requirements, is also presented. The analysis of scientific research work carried out on the economic and environmental significance of the transition to natural gas fuel in the conditions of global warming and reduction of oil reserves today is described.

1 INTRODUCTION

1.1 Overview of Fuels Used for Internal Combustion Engines

Many authors describe the main types of fuels, which are currently being used for automobile engines. They are Erokhov V.I. (Erokhov, 2003), Khachiyan A.S. (Khachiyan et al., 2008), Chernyshova N.D. (Chebykin et al., 2024), and Zongyu Yue (Yue et al., 2023) etc:

- Diesel fuel produced from petroleum; synthetic diesel fuel produced from mineral oils; semi-synthetic diesel fuel, consisting of various ratios of the above fuels; gasoline with various octane numbers;
- Fuels based on alcohols (wood, potato, corn, etc.), mainly used in China, Brazil and Argentina;
- Gas fuel based on various mixtures of propane and butane, produced from oil;
- Fuel based on natural gas with methane content from 80 to 99%, both in liquid and gaseous state (Khachiyan et al., 2010);
- Fuel based on synthesis gas CH3 (OH);
- Hydrogen fuels (Bryzgalov et al., 2009, Khachiyan et al., 2008, Umerov et al., 2024);

In addition to fuels, electrical energy from storage batteries, such as solar energy from cells, and mechanical energy from flywheels are used. These energies are not considered in this effort, since vehicles with internal combustion engines are used only for hybrid powertrains.

1.2 Promising Fuels for Vehicles

The most promising fuels in terms of environmental requirements according to Erokhov V.I. (Erokhov et al., 2011), Chernyshova N.D. (Chebykin et al., 2024 and others are natural gas, chemical formula CH_4; synthesis gas, chemical formula $CH_3(OH)$; hydrogen, chemical formula H_2.

To obtain zero toxicity of a car, hydrogen is usually oxidized in a special device called a "fuel cell", with the receipt of electrical energy used in electric motors.

Internal combustion engines cannot compete with electric motors in terms of zero toxicity (Cisek et al., 2022), because even when hydrogen is burned in air at a high temperature in the combustion chamber, in addition to water, nitrogen oxides NOx are formed. The absence of NOx emissions during combustion of

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hydrogen in an internal combustion engine is possible only when pure oxygen is used as an oxidizer. However, this is currently unacceptable due to the impossibility of storing a sufficient amount of oxygen on board the car. The use of hydrogen in road transport on a large scale requires significant material costs and new technologies, which have recently received the prospect of further development.

The use of synthesis gas is associated with the costs of obtaining it from natural gas and requires material costs, both for the development of such units and for the development of a network of filling stations, which will restrain its further use.

Natural gas is the most promising in terms of both economics and environmental performance. Natural gas can produce both synthesis gas and hydrogen. So that nowadays, natural gas is at the next step towards achieving the lowest emissions of toxic substances from internal combustion engines.

1.3 Changes in Environmental Requirements for Car

Every year the fleet of automotive vehicles is growing rapidly (Grigoriev et al., 1989). Accordingly, the amount of pollutant emissions from the exhaust gases of internal combustion engines is also growing. To maintain the balance of the Earth's atmosphere, harmful emissions should not exceed the capacity of natural phenomena to neutralize them. In this case, the bulk of the emissions should participate in the cycle of chemical components in wildlife. Plants using photochemical processes must absorb so all the CO_2 released from automobile engines. They are required to decompose it into carbon and oxygen. In this case, carbon participates in the process of building living organisms of nature, and oxygen is released into the atmosphere. Substances such as CO, CH, NO_x undergo redox processes on board with vehicles to transform them into naturally occurring substances (CO_2, H_2O, N_2). These substances in the earth's atmosphere should not increase in absolute and relative quantities. The process of tightening the standards of exhaust gas toxicity is natural (Fusshoeller et al., 2004).

2 MATERIALS AND METHODS

Reducing pollutant emissions can be achieved by various technical means used both to reduce the total consumption of hydrocarbon fuels, and for redox processes on board a vehicle Musabekov et al., 2023). Reducing the consumption of hydrocarbon fuels can be carried out as follows:

- by switching to a new type of environmentally friendly fuel or energy;
- improvement of energy conversion processes in internal combustion engines;
- transition to hybrid energy conversion schemes.

Redox processes on board a vehicle are usually carried out using the following:

- multicomponent neutralizers and collectors;
- chemical filters;
- electrical plasma converters.

Each change in environmental requirements in tightening leads to a complication of the design of both the engine itself and its systems: fuel supply, air supply, exhaust gas, oil, cooling, neutralization and control. All this together leads to a rise in the cost of the vehicle.

Tables 1 and 2 show the main characteristics of liquid and gaseous fuels.

Table 1: Physical properties of isooctane, motor gasoline, diesel fuel and liquefied propane as fuels for transport

Property	**Isooctane**	**Petrol**	**Diesel fuel**	**Propane**
Formula	C_8H_{18}	$C_4...C_{12}$	$C_{14}…C_{22}$	C_3H_8
Atom ratio H/C	2,25	2,03	1,63	2,67
Density at 15° C, kg/m^3	690,2208	746,54	880,75	579,9772
Net calorific value Hu, kJ/kg	44411,848	42912,076	40610,1	46411,54
Energy density, MJ/m^3	30,653981	32,035581	35,767346	26,917635
Stoichiometric number L_0 air/fuel (in mass numbers)	15,1	14,7	13,9	15,7
Octane number	100	80-98	Cetane number 40-60	105
Stoichiometric energy mixes E, kJ / kg Ev, MJ / m^3	2757,720	2732,142	2725,167	2780,972
	1,903436	2,039653	2,400191	1,6129
Evaporation temperature, K	398,15	302,6...477,6	458,1.610,9	230,93
Saturated vapor pressure (kPa)	55,16	45-105	1,38	1420,33 (1)
Flammable limits lower (% by volume) upper (% by volume)	1,4	1,4	1	2,2
	7,6	7,6	6	9,5

Stoichiometric mixture energy, kJ / kg stoichiometric mixture:

$E=Hu/(1+L_0)$ or in kJ/m^3 stoichiometric mixture $E_v=E_p$, where p is the density in kg/m^3.

1. The critical temperature of propane is 369.817 K, the critical pressure is 4247.2 kPa.

The important parameters of gasoline as a fuel are: the amount of energy (net calorific value) per unit of mass and unit of volume, volatility and octane number (Enomoto et al., 2023). Mass and volume indicate the capacity of the fuel needs to be conveniently placed on board the vehicle.

The volatility of the fuel is important in a vehicle during cold start of the engine in order to obtain the required air-fuel mixture. Currently, fuel volatility is critical for exhaust emissions and fuel evaporation from tanks in warm weather.

The octane number is indicative of the ability of the fuel to prevent the occurrence of premature ignition (detonation) of the air-fuel mixture in the engine cylinders when the mixture is compressed in the engine cylinders and, consequently, to its efficiency.

Table 2: Physical properties of ethanol, methanol, methane and hydrogen as alternative fuels for transport

Property	Ethanol	Methanol	Methane	Hydrogen
Formula	C_2H_5OH	CH_3OH	CH_4	H_2
Atom ratio H/C	3	4	4	-
Density at 15° C, kg/m^3	788,4814	790,878	0.672756	0.0864972
Net calorific value, Hu, kJ/kg	26707,564	19903,948	50108,655	120028,25
Energy density, MJ/m^3	21,058	15,742	21,256	8,486
Stoichiometric number L_0 air/fuel (mass number)	9,0	6,5	17,3	34,5
Octane number	101	100	129	60
Stoichiometric energy mixture E, kJ/kg	2690,288	2669,361	2750,744	3380,881
Ev, MJ/m^3	2,121	2,111	1,167	0,239
Flammable limits lower (% by volume)	4,3	7,3	5,3	4,1
upper (% by volume)	19	36	15	74

3 RESULTS AND DISCUSSION

Ethanol can be used straight as a motor fuel in three ways:

- 100% ethanol;
- from 5 to 15% ethanol mixed with gasoline;
- Hydro-ethanol, consisting of 95% ethanol and 5% water.

Direct use of ethanol, in the above three ways, as a vehicle fuel has both advantages and disadvantages. Because the high latent heat of vaporization of ethanol results in a lower combustion temperature in the engine cylinder.

It should be noted that alcohols methanol and ethanol are not desirable to be used as additives in gasoline, because they increase the saturated vapor pressure of the mixture more than that of pure gasoline. This increases the emission of gases into the atmosphere. However, the gains in exhaust gas emission reductions that can be achieved with these alternative blends of gasoline and alcohols are very small compared to those that can be achieved with hydrogen or natural gas (Norouzi et al., 2021).

3.1 Natural Gas as Fuel for Vehicles

Natural gas (Erokhov et al., 2003) is a gaseous mixture of light hydrocarbons, mainly methane and ethane, and other gases found in the atmosphere of our planet. In the early stages of the development of the oil and gas industry, natural gas was obtained as a by-product from the production of liquid fuels and hydrocarbons for the chemical industry from oil. Currently, from 3 to 5% of natural gas is obtained in the above-mentioned industries, the rest consists of approximately 10 to 20% obtained from oil wells and from 75 to 87% from individual wells. Natural gas found with oil can contain pentane and gasoline constituents as well as propane and butane. This gas is classified as a "wet" gas containing heavy hydrocarbons. In the course of processing, the gas condensate part is separated from it and "dry" gas is obtained. The composition of natural gas varies considerably from field to field.

Natural gas contains: propane, butane, pentane, heavy hydrocarbons, hydrogen, oxygen, carbon dioxide, nitrogen and helium (rarely found in small quantities). Propane and butane are known as liquefied petroleum gas (LPG or LPG), while pentane and heavy hydrocarbons are known as natural gasoline. Carbon dioxide, nitrogen and helium - inert gases must be removed in order to improve the energy value of natural gas.

When the fuel is ignited in the cylinder, hydrogen creates active centers that improve the combustion process. Therefore, the hydrogen content in natural gas should be optimal from 6 to 8%, according to the data by Bryzgalov A.A., Smolensky V.V. and Shaikin A.P. (Bryzgalov et al., 2009, Umerov et al., 2024). Natural gas, which is an odorless gas, is odorized prior to distribution to the consumer to provide a distinctive aroma that warns customers of potential leaks. At normal atmospheric pressure, the density of natural gas is too low, and therefore the energy supply in this case will not be sufficient on board the vehicle. To ensure the required supply of natural gas on board the vehicle, it is necessary to compress (compress) to 20 either MPa or 80 MPa and place it in a high-pressure vessel, or cool it to a liquid state and fill it into a cryogenic tank.

One of the positive characteristics of natural gas as a vehicle fuel is its high octane number from 125 to 130, which depends on the chemical composition of the natural gas. This allows it to be used in engines with high compression ratios from 11.5: 1 to 15: 1. Due to this, the combustion efficiency improved with obtaining maximum work, the power indicators of the engine can be even higher than when running on gasoline from 3 to 5%.

The main advantages of natural gas and methane as motor fuels (Malyshev et al., 2008):

- reducing the wear of the connecting rod-piston group of the engine increases the engine resource;
- increase in engine overhaul mileage;
- an increase in the resource of spark plugs;
- increase in the service life of engine oil;
- lack of detonation;
- reduction of emissions of carbon dioxide and toxic components in exhaust gases;
- a decrease in the vibration component of the engine due to a decrease in the combustion rate of methane and, accordingly, a decrease in the rate of pressure rise in the combustion chamber.

Problems hindering the rapid introduction of natural gas in modern transport, in contrast to gasoline and diesel fuel:

- internal unavailability of the natural gas infrastructure for the possibility of replacing existing motor fuels (insufficient number of CNG filling stations);
- insufficient supply of natural gas on board the vehicle;
- lack of mass serial production of components for gas equipment that meets modern safety requirements, gas fuel vapor and exhaust gas toxicity;
- lack of mass serial production of vehicles running on natural gas;
- consequences for the environment during the transportation and use of natural gas;
- economic aspects of natural gas as a fuel.

3.2 Economic Feasibility of Switching to Natural Gas

The economic efficiency of natural gas is shown in many works by Erokhov V.I. (Erokhov et al., 2003), Kapustina A.A. (Kapustin et al., 2011), V.V. Malysheva. (Llotko et al., 2000), D.V. Pasechnika. (Matmurodov et al., 2024), Pevneva N.G. (Pevnev, 2010, Pevnev et al., 2010), Rovner G. (Rovner, 2006), Teremyakina P.G., Khachiyan A.S., (Teremyakin et al., 2011), Chernyshova N.D. (Chebykin et al., 2024) and others. However, this has not yet become the impetus for its mass introduction in transport. Economic efficiency is determined by the price of natural gas and its restrictions by government agencies. The price of gas is made up of costs: for prospecting a field, its appraisal, drilling a well, building compressor stations for pumping gas, building pipelines for transporting and distributing gas, etc. These costs are significantly lower than the costs of oil extraction and processing into motor fuels.

The second obstacle to the slow introduction of natural gas in transport as a vehicle fuel is the high cost of components for storing it on board. These components include high pressure cylinders and cryogenic tanks. The price of the rest of the fuel equipment is commensurate with the price of equipment for other types of fuels and does not significantly affect the use of natural gas.

4 CONCLUSIONS

At present, when the price of natural gas is limited to half the cost of gasoline with an octane rating of 76, it allows the consumer to achieve savings from 3 to 3.5 times per 1 km of vehicle mileage. With such a difference, even with the high cost of cylinders, the payback period for light vehicles is from 25 to 30 thousand km and for trucks and buses about one year.

The advantages of natural gas in relation to other types of fuel at the present stage of development:

- low price;
- the density is less than that of air, this ensures the safety of its use due to its escape into the upper layers of the atmosphere;
- the ratio of hydrogen atoms to carbon atoms is 4: 1, which, in comparison with gasoline, reduces CO2 and CO emissions in exhaust gases by up to 28%;
- the high value of the net calorific value provides, in comparison with gasoline and diesel fuel, the preservation and, in some cases,

an increase in engine power and torque (with an optimal compression ratio, a high degree of filling the cylinders with a fuel mixture, optimal ignition parameters);
- low burning rate, in comparison with gasoline, ensures smooth operation of the engine and, accordingly, increases its resource;
- high knock value from 125 to 130 ensures reliable engine operation in all modes with high efficiency;
- is an environmentally friendly, renewable fuel using plant residues for its production;
- when used in a compressed state (CNG), a pump and an evaporator are not required to feed the internal combustion engine into the combustion chamber. When using wet gas, a minimum heating of the reducer valve pair is required to reduce the pressure.

Disadvantages of natural gas as a fuel and ways to minimize them:

- storage on board a vehicle under high pressure or at cryogenic temperatures, or in an adsorbent increases the weight of cylinders or tanks, fuel equipment and its fasteners;
- low combustion temperature, in comparison with gasoline, increases the heating time of the collector or neutralizer;
- causes the greenhouse effect in the earth's atmosphere, for which it is required to minimize its leakage from fuel systems and emission from the combustion chamber during the start of an internal combustion engine;
- when used in a liquefied state in cryogenic cylinders, drainage into the atmosphere is required to prevent an increase in pressure in the cryogenic cylinder above the working one.

To reduce the weight of fuel equipment cylinders, new materials have recently been used: aluminum alloys, resin-impregnated fibrous synthetic materials, stainless steels and super-strong steels, titanium alloys - to obtain the required margin of safety. In addition, the use of one cylinder of the same volume, instead of several on the vehicle, also reduces their overall weight.

To accelerate the heating of the catalyst, several methods are currently used, these are:
- reducing the distance between the catalyst and the exhaust valves of the engine;
- warming up the engine after starting is carried out on lean mixtures to increase the afterburning temperature of natural gas (excessive depletion in the warm-up mode can lead to a significant increase in NOx emissions in the exhaust gases);
- an increase in the content of hydrogen molecules in natural gas, which increases the number of active ignition centers, and therefore increases the combustion rate and temperature of the exhaust gases;
- decomposition of methane molecules into radicals of hydrogen and carbon, and oxygen molecules into radicals of oxygen atoms before ignition, which also increases the combustion rate of the fuel mixture and its temperature;
- increasing the pressure in the combustion chamber before ignition, by increasing the compression ratio, leads to an increase in the initial ignition temperature and, accordingly, the combustion temperature.

To minimize methane emissions into the atmosphere, the following measures are applied:

- special seals of pipelines and fittings, reducing the likelihood of depressurization;
- use of a gas leakage monitoring system, which signals about malfunctions and automatically gives a command to shut off the gas valve to stop gas fuel leaks;
- the use of catalysts for the oxidation of methane to CO_2 and H_2O and excluding its release into the atmosphere;
- optimization of gas consumption at engine start and depletion of the mixture during its warming up reduces methane emissions through exhaust valves for engines with simultaneously open intake valve;
- direct injection of gas into the combustion chamber during compression, when both valves (intake and exhaust) are closed;
- increasing the completeness of natural gas combustion with the help of: various constructive measures for the combustion chamber, for the fuel mixture preparation system and for the ignition system;
- reduction of misfire and inefficient combustion in combustion chambers by increasing the energy given off by the ignition coils.

To reduce the amount of methane emitted through the drainage of the cryogenic cylinder, it is necessary:

- a catalyst is installed in the drain for the oxidation of methane to CO_2 and H_2O and to prevent it from entering the atmosphere;
- increase the degree of evacuation of the volume of the cryogenic cylinder insulation;

- increase the degree of thermal insulation of the inner vessel using special construction materials (materials with low thermal conductivity, mirror multilayer foil, etc.);
- increase the strength of the walls of the inner vessel to increase the working pressure and increase the time without drainage storage.

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