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Improving Fuel Efficiency and Environmental Performance Indicators of Light Vehicle Engines

J.F. Ismatov[1][a], J.X. Djalilov[2][b], Z.E. Musabekov[1][c], J.O. Xakimov[1][d] and R.R. Tillahodjayev[1][e]

[1]*Department of Mechanical engineering, Tashkent State Technical University, Tashkent city, Uzbekistan*

[2]*Department of Automotive transport engineering, Tashkent State Transport University, Tashkent city, Uzbekistan*

Jumaniyoz132@mail.ru, Javlon.djalilov@gmail.com, zokirmusabekov@gmail.com, khakimov-jamshid@mail.ru, rustam29031965@gmail.com

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Abstract: Conducting scientific research aimed at increasing the fuel efficiency of vehicles and enhancing their environmental safety through the use of renewable energy sources has become critically important worldwide. In this regard, priority is given to studies focused on modernizing vehicles with minimal modifications to their structural parameters based on real operating conditions, as well as reducing transportation costs and the negative environmental impact of vehicles through the use of environmentally friendly fuels.

1 INTRODUCTION

Improving the operating efficiency of internal combustion engines—considered the primary power units of automotive transport—through the evaluation of real-world operating conditions and the selection of engine operation modes adapted to specific usage scenarios is a pressing research task. This includes exploring methods to enhance energy efficiency and the use of alternative fuels.

In Uzbekistan, the use of hydrogen as an additional fuel for light vehicles currently in operation presents a promising opportunity to improve their technical and economic efficiency. To this end, comprehensive and strategic measures are being implemented to promote the rational use of environmentally clean and highly efficient renewable energy sources.

The adoption of various regulatory and legal frameworks supporting scientific and methodological work in the field clearly demonstrates the country's commitment to ensuring environmental and energy security in the transport sector. Notably, the Development Strategy of New Uzbekistan for 2022-2026 outlines specific objectives, such as ensuring the uninterrupted supply of oil and gas products to the economy and the population, and assessing the impact of Uzbekistan’s accession to the World Trade Organization on industries like metallurgy, textiles, food production, and automotive manufacturing.

To achieve these goals, it is essential to consider the role of transportation-particularly automotive transport-in the national economy. Therefore, conducting systematic research on increasing fuel efficiency, reducing the environmental impact of vehicles, and developing appropriate assessment methodologies for these parameters is of high importance.

Furthermore, emission standards for harmful substances in vehicle exhaust gases (such as CO, CH, NOx, and PM) are being continually tightened (Euro-3 in 2005; Euro-5 in 2008; Euro-6 in 2015). Reducing these hazardous emissions is fundamental to preventing the ecological and chemical dangers posed by automobiles, especially considering that highly toxic and carcinogenic hydrocarbons (HC) and their derivatives, which pose serious health risks to humans, remain largely unregulated [2, 3, 4, 5].

[a] https://orcid.org/0000-0001-5367-5552
[b] https://orcid.org/0000-0001-5169-1102
[c] https://orcid.org/0009-0006-3435-8774
[d] https://orcid.org/0000-0001-9139-1753
[e] https://orcid.org/0000-0003-4137-1273

2 MATERIALS AND METHODS

Currently, in the global energy balance, internal combustion engines-used as the primary power units in land transportation and transport-technological systems-occupy a leading position in terms of energy production.

The tightening energy efficiency and environmental requirements for vehicles necessitate the search for innovative and forward-looking directions and methods to improve fuel economy and environmental performance during vehicle operation. Achieving resource efficiency and meeting ecological standards in transportation can be accomplished by addressing technological, organizational, and structural issues, taking into account all influencing factors.

The key quality indicators of fuels that ensure the reliable operation of internal combustion engines must comply with state standards or technical specifications. Therefore, these fuels must be produced and used within specific regulatory frameworks.

Traditional liquid fuels (gasoline and diesel) and gaseous fuels (compressed natural gas and liquefied petroleum gas), which are most commonly used in internal combustion engines, possess distinct physical-chemical and operational properties. Physical-chemical characteristics that describe a set of properties such as density, viscosity, fractional composition, and chemical stability are typically determined under laboratory conditions.

The operational properties of engine fuels-including production, transportation, storage, testing, and utilization-define their effectiveness for intended use and, consequently, determine the scope of application for these products.

The main energy parameter of an internal combustion engine is its power output, which depends on the energy characteristics of the fuel used, particularly its calorific value. The heat released during the combustion of the fuel-air mixture varies significantly depending on the excess air coefficient or the composition of the combustible mixture [6, 7, 8].

Globally, alternative fuels used in internal combustion engine-powered vehicles include the following:

- Methanol, denatured ethanol, and other alcohols;
- Blended fuels containing at least 70% (typically 85%) alcohol mixed with gasoline or diesel fuel;
- Methane or natural gas (compressed or liquefied);
- Liquefied petroleum gas (LPG);
- Hydrogen;
- Biogas;
- Biofuels;
- Oils;
- Coal and other alternatives.

At present, the production of alternative fuels aside from petroleum is receiving growing attention. Among these, methanol, hydrogen, and ammonia are attracting the most interest [9].

Despite the numerous discussions surrounding the advantages of hydrogen, its real-world application remains limited. Nevertheless, many projects are being developed, and the objective of this research is not only to discuss hydrogen as an ideal fuel but also to explore its practical implementation. This topic is highly relevant today, as environmental concerns and potential solutions are of increasing importance not only to our country but also to the global population.

Hydrogen technology refers to the industrial methods and means for producing, transporting, and storing hydrogen, as well as the tools and approaches for its safe use, based on inexhaustible raw material and energy sources.

The adoption of hydrogen for combustion in transportation, industry, and everyday life offers a fundamental solution to the issue of air pollution caused by oxides of carbon, nitrogen, sulfur, and hydrocarbons.

Transitioning to hydrogen technologies and utilizing water as the sole raw material for hydrogen production does not pose a threat to the planet’s overall water balance or that of specific regions. For example, the annual energy demand of a highly industrialized country such as Germany can be met using hydrogen produced from a volume of water equal to just 1.5% of the average flow of the Rhine River.

Hydrogen derived from water is one of the most energy-rich carriers. Specifically, the lower heating value of 1 kg of H_2 is 120 MJ/kg, compared to 46-50 MJ/kg for gasoline or even the highest-grade hydrocarbon-based aviation fuel-making hydrogen approximately 2.5 times more energy-dense. Additionally, hydrogen is considered a readily renewable fuel source.

Water electrolysis has long been practiced in industrial applications and is extensively described in the literature. Currently, significant scientific and industrial efforts are being made to utilize the inexhaustible energy of solar radiation for water splitting. This includes the use of photolysis cells for water decomposition, solar panels for generating electricity, and subsequently using that electricity for electrolysis. The central task in this process is to conduct a series of photochemical reactions aimed at directly splitting water into hydrogen and oxygen under the influence of solar energy. The core challenge lies in identifying biological systems capable of utilizing solar energy to decompose water.

The only by-product of hydrogen combustion is water vapor, which naturally re-enters the Earth's water cycle. And, as is well known, hydrogen can again be obtained from water via electrolysis. This closed cycle, which underpins the concept of hydrogen energy, makes hydrogen one of the most environmentally friendly fuels available.

Clearly, the transition of transport systems to hydrogen fuel could entirely resolve the environmental issues faced by large cities. However, this transition is hindered by several challenges, including:

- The high energy demand required to produce hydrogen through water electrolysis;
- The need for specialized, ultra-sealed containers for storing and transporting hydrogen, due to its small molecular size and high permeability.

Moreover, using hydrogen in conventional internal combustion engines (with appropriate modifications) not only ensures cleaner operation but also improves thermal efficiency and enhances engine adaptability.

The use of hydrogen fuel in light vehicles is of great significance in terms of energy efficiency, fuel economy, and environmental sustainability. Table 1 presents the thermos-physical properties of alternative and conventional motor fuels.

Table 1: Thermophysical Properties of Alternative and Conventional Motor Fuels.

Property / Fuel Type	Gasoline (Benzin)	Diesel	Methanol	Hydrogen
Density in Liquid State, kg/m³, at p=1.013 bar and temperature t, °C	750-770 15	820–845 15	423 -162	70,8 -253
Density in Gaseous State, kg/m³, at p=1.013 bar; t=0 °C	-	-	0,716	0,090
Molar Mass, kg/kmol	≈98	≈190	16,043	2,016
Boiling Point Tempe-rature (or Range), °C, at p = 1.013 bar	30 – 190	210 – 355	-161,5	-252,8
Stoichiometric Air Requirement, kg of air per kg of fuel volume, %	14,0 –	14,7 –	17,2 9,5	34,3 29,5
Lower Heating Value of the Fuel, kJ/kg	44000	42 900	50 000	120 000
Energy Intensity, kJ/dm³: - In liquid state at p = 1.013 bar - In gaseous state at p = 350 bar, T = 280 K	31700 –	35800 –	21000 12600	8500 3 000
Heat of Combustion of a Combustible Mixture, kJ/m³, with premixed external mixture formation, p = 1.013 bar; t = 0 °C; $\alpha_v = 1$	3 830	3 770	3 760	4 520
Flammability Li-mits in Air p=1.013 bar; t=25 °C: – volume % – range of α_v	1-7,6 1,4-0,4	0,6-5,5 1,35-0,48	4,4–15 2,28-0,6	4–76 10-0,13
Auto-Ignition Temperature in Air, °C, at p = 1.013 bar	230-450	250	595	585
Minimum Ignition Energy in Air, mJ, α_v=1	0,24	0,24	0,29	0,017
Diffusion Coeffi-cient in Air, m²/s: -p=1.013 bar; t=0°C -p=100 bar; T=1000 K	510-6 –	– –	1610-6 1,910-6	6110-6 8,510-6
Laminar Flame Speed in Air, m/s, p=1.013 bar; t=25 °C; α_v=1	0,4	0,4	0,42	2,30
Research Octane Number (RON)	98	-	130	-
Methane amount	88	-	100	0
Cethane amount	-	52-54	-	-
Mass fraction of components, %				
C	85,6	86,1	74,9	0
H_2	12,2	13,9	25,1	100
O_2	2,2	0	0	0

It has already been noted that the use of hydrogen as a substitute for petroleum-based fuels in internal combustion engines offers several undeniable advantages, such as a carbon cycle characterized by minimal oxidation duration due to the rapid formation of radicals that activate oxidation reactions. Compared to gasoline and diesel, hydrogen's favorable carbon-to-hydrogen (C:H) ratio and superior anti-knock properties also contribute to the implementation of low-carbon technologies in transportation.

In general, the study of how any motor fuel-including hydrogen-affects the performance of a spark-ignition internal combustion engine in light vehicles is closely tied to the fundamental source data: the primary physical-chemical, thermos-physical, thermos-technical, and other relevant properties of the fuel under investigation (*see Table 2*).

Table 2: Thermo-physical properties of various alternative fuels.

Properties	Hydrogen	Methanol	Propane	Buthanol	Ethanol
Combustion at Low Energy, MJ	0,018	0,28	0,25	0,25	0,24
Ignition Limits	0,14÷2,54	0,53÷1,6	0,57÷2,5	0,5÷2,9	0,53÷2,2
Heat of Combustion, MJ/kg	120	50	47	49,5	48
Maximum Flame Propagation Speed, cm/s	325	44,8	46,4	45	47,6

In the organization of combustion processes in internal combustion engines, the value of the normal flame propagation speed and its statistical characteristics play a crucial role. The duration of the combustion process, the temperature and pressure within the cycle, and consequently, the engine's efficiency, depend on the average combustion speed. Random deviations from the average value define cycle-to-cycle variations in the combustion process, the extent of which is limited by the effective composition range of the air-fuel mixture. Operating with lean mixtures is considered a promising method for improving the fuel efficiency of spark-ignition internal combustion engines [9].

The necessary thermodynamic parameters for different gases can be determined from relevant literature sources [10, 11,12, 13] (*see Table 3*).

Table 3: Burning rate of alternative fuels at different excess air ratios.

Gaz	Normal Flame Speed, cm/s				Maximum Value
	α=0,8	α =1,0	α =1,2	α =1,4	
Hydrogen	320	230	150	120	320 cm/s α=0,8
Methanol	30	43,4	39,8	-	44,8 cm/s α=1,08
Propane	32	44	43,	28	46,4 cm/s α=1,06
Buthanol	38	44,8	41,2	25,0	44,9 cm/s α=1,03
Ethanol	36	44,5	47,3	37,4	47,6 cm/s α=1,14

From the above table, it can be observed that the flame speed of hydrogen is significantly higher than that of other gaseous fuels. When compared with methane and propane, which are currently the most widely used gaseous fuels in our country, the flame speed of hydrogen is nearly eight times greater.

3 RESULTS AND DISCUSSION

For For the F16D3 engine of the GM Chevrolet Cruze/Aveo/Lacetti light vehicle, calculations were carried out by adding hydrogen to the gasoline-air mixture under the following conditions:

- Primary reference fuel – AI-91 gasoline
- Supplementary fuel – hydrogen at concentrations of 5%, 10%, and 15%.

According to the developed methodology for calculating light vehicle performance indicators, the process was implemented using a modified Microsoft Excel tool, which allows for simultaneous parallel calculations of engine performance when hydrogen is added to the gasoline-air mixture in proportions ranging from 5% to 50% of the total motor fuel.

This approach enables the selection of appropriate initial parameter values and facilitates the analysis of the obtained comparative results.

The generalized comparative results of the calculated engine performance parameters are presented in Table 4.

Table 4: Generalized comparative results of the calculated performance parameters of the internal combustion engine.

Name	Unit of Measurement	Gasoline + Hydrogen Fuel			
		Gasoline Ai-91	5%	10%	15%
Rated Power	kVt/min^{-1}	80/5800	80,7/5800	80,5/5800	80,6/5800
Torque	Nm/min^{-1}	150/3600	159/2200	158,7/2200	158,9/2200
Hourly Fuel Consumption	kg/s	19,2	19,1	18,7	18,4
Specific Fuel Consumption	g/kVt·s MJ/kVt·s	240,36	236,89	232,62	228,60
Lower Heating Value of the Fuel	MJ/kg	44	44,7	45,4	46,2
Theoretical Air Requirement for Complete Combustion	kg/kg	14,96	15,15	15,5	15,7
Mean Effective Pressure	MPa	1,04	1,044	1,046	1,05
Effective Thermal Efficiency (Brake Thermal Efficiency)	%	0,3409	0,3402	0,3407	0,3411

The operational efficiency of vehicles largely depends on the properties of the motor fuels used in their internal combustion engines. Hydrogen is widely used as a fully environmentally friendly alternative (either fully or partially) to gasoline. Moreover, the classification of an alternative motor fuel is often demonstrated through the partial substitution of gasoline with hydrogen.

4 CONCLUSIONS

The addition of hydrogen to the gasoline-air mixture is primarily applied as a motor fuel for spark-ignition internal combustion engines, offering modern and highly efficient fuel characteristics.

A comparative analysis of the properties of hydrogen-enriched gasoline-air mixtures shows that using a gasoline-air-hydrogen blend in spark-ignition internal combustion engines of light vehicles is an effective solution for increasing the use of clean gaseous resources. It also serves as a scientifically grounded and technically viable approach for producing efficient motor fuel while contributing to environmental protection.

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