Analysis of using hydrogen in the internal combustion engines of motor vehicles to increase operational efficiency

V N Konoplev¹, Z G Melnikov¹, A S Korzin¹ and N A Khripach²
¹RUDN University, Miklouho-Maclay Street, 6, 117198, Moscow, Russia
²MAMI (Moscow Polytech), Bolshaya Semenovskaya, 38, 107023, Moscow, Russia

E-mail: konoplev_vn@pfur.ru

Abstract. This paper examines the research and experiments on the use of hydrogen in transport to improve the energy efficiency of internal combustion engines (ICE) of motor vehicles (MV). Models of electrochemical hydrogen generator sets and modules with intermetallic compounds TiFeV onboard MV and technical measures for the correction of the engine control system algorithm are proposed.

1. Introduction

In accordance with the fifth law of thermodynamics, those technical systems that have an increased value of efficiency receive priority development. And taking into account the requirements of the present time, they also receive the environmental cleanliness of the exhaust gases of power plants [1]. One of the most promising areas is the production on board of a vehicle and the usage of hydrogen, as well as chemical gas compounds based on hydrogen in the function of fuel or as an additive to the fuel-air mixture - fed to the combustion chambers of an internal combustion engine. The effectiveness of the usage of hydrogen is explained by its high heat of combustion (Table 1) among the substances used as energy carriers and currently used substances. For comparison, heat of combustion of gasoline and diesel fuel is 42-44 MJ/kg, and methane is 50 MJ/kg [2], that is, more than two times less than that of hydrogen (Table 1). An indicator such as a heat of combustion affects the specific fuel consumption and thus makes it possible to increase the efficiency of the engine. In addition, hydrogen is an activator of reducing NOx emissions in the composition of the exhaust gases, which is important for modern tightening of environmental standards regulating the content of harmful substances in the composition of exhaust gases (EG). For example, it was found that hydrogen has a positive effect on the processes of oxidation and soot release in diesel engines. The presence of hydrogen in the reaction zone and the combustion of the air-fuel mixture (AFM) is accompanied by redox reactions of nitrogen [3]:

\[2\text{NO} + 2\text{H}_2 \rightarrow \text{N}_2 + 2\text{H}_2\text{O}.

It should also be noted that, according to the results of studies [4], along with a decrease in NOx emissions with a portion addition of methanol conversion products ~ 10% (with a hydrogen content of ~ 1.25%) in a diesel engine fuel assembly - there was a decrease in soot content in the exhaust gas by 45% in the entire range of load modes. In connection with the foregoing, hydrogen can rightly be considered one of the most promising energy carriers for large-scale use in vehicles. However, there are a number of problems, including the following:

- the lack of a developed infrastructure for storing hydrogen in order to refuel MVs using it as fuel;
the relatively high cost of producing pure hydrogen;
• adverse impact on the environment caused by the manufacturing capacity in the production of pure hydrogen due to the usage of the technology of steam reforming of natural gas or oil fractions;
• the high safety requirements for the technical design of equipment for transportation, storage under pressure or in a bound state with intermetallic compounds, hydrogen supply to the combustion chamber of the internal combustion engine.

Table 1. Used energy of fuel mixtures in different modes of movement of the truck ZIL-431410 * [1].

| Driving mode                  | Fuel A-76, MJ | Hydrogen supply in the engine partial load modes, MJ (M ≤ 0.65 Mmax) | Hydrogen supply in the entire engine operating space, MJ |
|-------------------------------|--------------|------------------------------------------------------------------|--------------------------------------------------------|
| Urban driving cycle           | 1470.0       | 1434.0                                                           | 1387.0                                                 |
| \( V_{\text{const}} = 40 \text{ km/h} \) | 856.5         | 816.0                                                            | 857.6                                                  |
| \( V_{\text{const}} = 60 \text{ km/h} \) | 1035.5        | 926.0                                                            | 974.0                                                  |
| \( V_{\text{const}} = 80 \text{ km/h} \) | 1268.8        | 355.2                                                            | 1120.4                                                 |

*Note: when calculating, the density of gasoline was assumed to be 0.727 kg/l; hydrogen – 0.09 kg/m³; net calorific value of gasoline – 44.2 MJ/kg, hydrogen – 112.0 MJ/kg.

2. Materials and methods

There is an interesting experience of joint testing of GATS ZIL-431410 equipped with a special power supply system, a hydrogen storage system in metal hydride batteries based on an intermetallic compound – TiFeV, and instrumentation (Figure 1) for determining power consumption, speed properties and operational characteristics. The total mass of the four modules, filled and fueled with hydrogen, was 255 kg (excluding the connecting fittings from the battery fastening elements and the vehicle weight).

![Figure 1. Scheme of the gas supply system and instrumentation of the truck ZIL-431410: 1 – Carburetor mixer; 2 – Hydrogen reducer; 3 – Electromagnetic valve supplying hydrogen to the gearbox; 4 – Block of test gauges; 5 – Voltage converter; 6 – Water-supply manifold; 7 – Hydrogen exhaust manifold; 8 – Hydrogen valves; 9 – Common safety valve; 10 – Safety valves of the hydride system; 11 – Electromagnetic valve of a hydrogen (dimensional) cylinder; 12 – High pressure reducer; 13 Cylinder for storing hydrogen under pressure of 20 MPa; 14 – Shut-off valve; 15 – Instrument case of the temperature measurement device (TMD); 16 – Gasoline flow meter; 17 – Mode relays of hydrogen supply; 18 – Gasoline pump; 20 – Bypass (engine cooling system); 21 – Radiator.](image)
1) without the dosage of hydrogen;
2) with a dosage of hydrogen at partial load mode of the engine (M < 0.65 Mmax);
3) with the dosage of hydrogen in the entire working mixture (from nxx to M max).

The engine power supply system in hydrogen dosage modes ensured engine operation with gasoline-poor mixtures $\alpha_0 = 1.4 - 1.6$. Simultaneously, the working area with a specific consumption of not more than 300 g/kW has significantly expanded - more than 3 times (Figure 2).

![Figure 2. The operational field of the engine ZIL-431410.](image)

3. Results and discussion

The test results (Table 1) when the vehicle was moving along the urban driving cycle (GOST 203016-91) showed that due to the dosage of hydrogen in partial engine load modes, it is possible to replace up to 8% of gasoline, and in the case of hydrogen dosage in the entire working area of the engine up to 17.2%.

At the same time, the usage of thermal energy is reduced by 2.4 and 5.6%, respectively. In the case of driving a car at constant speeds, gasoline savings due to the addition of hydrogen reach 11-24%, depending on the dosage regimes of hydrogen and the speed of the vehicle. In the case of driving a car with $V_{\text{CONST}} = 80$ km/h and the dosage of hydrogen in partial load modes, an increase in the use of total energy by 6.8% was observed. This deterioration of the efficiency of the engine is explained by non-optimal law of the control of the electromagnetic valves supplying gasoline and hydrogen. When the vehicle was moving along the HEC, 1 liter of gasoline accounted for 0.18 m³ of hydrogen; based on this, the need for hydrogen per one gas station refueling (175 liters) is 31.5 m³. The determination of the possibility of improving the efficiency of the combustion process by varying the magnitude of the installation ignition timing angle $9^\circ$ and $15^\circ$ was carried out on a stand with chassis dynamometers while simulating the movement of a car with $V_{\text{CONST}} = 60$ km/h. According to the test results, it was noted that an increase in the ignition timing angle makes it possible to reduce the consumption of gasoline and hydrogen by 4.9 and 13.0%, respectively. In addition, data were obtained (Table 2) [1], confirming a significant reduction in toxicity (from 17 to 96%) of the exhaust gases of a gasoline engine when dosing hydrogen into the fuel-air mixture and increasing the load.
### Table 2 Comparison of emissions of toxic components of the internal combustion engine in the dosage of hydrogen compared with the those of the internal combustion engine working on gasoline A-76 * [1]

| Load conditions on stand drums P, kgs | Toxicity levels | Degree of change, % |
|--------------------------------------|----------------|---------------------|
|                                      | V=15 km/h      | V=45 km/h (Δ=30 km/h) |
|                                       |                |                     |
| 162                                  |                |                    |
|                                       | CH, ppm        | +100 +17            |
|                                       | NO, ppm        | +89 +96             |
|                                       | NO₂, ppm       | +90 +96             |
|                                       | CO₂, %         | +41 +43             |
|                                       | CO %           | +86 +75             |
| 192                                  | CH , ppm       | -14 +20             |
| (Δ=30 kgs)                           | NO, ppm        | +86 +80             |
|                                       | NO₂, ppm       | +83 +80             |
|                                       | CO₂, %         | +40 +41             |

+ the advantage of working on H₂; – the advantage of working on gasoline; * Stand test with chassis dynamometers

Replacing gas cylinder equipment for storage under a pressure of 20.0 MPa and a system for dozing hydrogen fuel or modules with intermetallic compounds onto equipment – capable of producing hydrogen on board a vehicle - simplifies the design of the power plant and reduces the vehicle mass by 250 kg.

These requirements are met by the method of producing a hydrogen mixture through its electrochemical conversion. This happens due to the flow of redox reactions on the electrodes immersed in the electrolyte (water or chemical solution), when a direct electric current passes through them. Moreover, this electrochemical process is accompanied by the release of oxygen O₂ at the anode and hydrogen H₂ at the cathode. Thus, at the output, we obtain a gas mixture at a ratio of 2: 1, i.e. two moles of hydrogen to one mole of oxygen. In order to ensure the required performance (gas emission), plates of different polarities are assembled into separate cassettes and connected in series, taking into account their polarity, coating and overall dimensions. Such assembly is an electrolyser (Figure 3). The electrolyte for it is dilute highly concentrated alkali (usually sodium hydroxide NaOH) in an aqueous solution. The produced gas from the electrolyser 5 is discharged through the connecting line to the reservoir with electrolyte 4 and then fed to the fine filter 3 (a membrane that absorbs the aerosol suspension of the electrolyte). After that, the gas enters the intake manifold of the combustion chamber of the internal combustion engine through the gas supply nozzle 2.

![Figure 3. Installation diagram of the electrolyser and its components in the power supply system of the internal combustion engine: 1 – module ignition; 2 – gas supply fitting into intake manifold; 3 – fine gas filter; 4 – tank with electrolyte; 5 – electrolyser; 6 – electronic control unit; 7 – throttle.](image-url)
According to experimental studies and safety analysis [4-6], the use of an electrolyser with a capacity of 20 l/h for engines with a swept-volume capacity of 1.5-3.0 liters, when working in the urban cycle, led to a significant reduction in fuel consumption by test vehicles from 25 % and more. In addition, it should be noted that hydrogen production using an electrolyser on board a vehicle is an energy-consuming process: for maximum performance of the electrolyser (2-2.5 l/min) on board a car with an engine swept-volume capacity of 1.5-2.5 l power consumption should be about 400 W of electrical energy (current will be about 30 A) [2].

4. Conclusion
In view of the foregoing, the following conclusions on the use of hydrogen in fuel mixtures of the internal combustion engine can be drawn:

1. Experimental results on trucks and cars confirmed the fundamental possibility of reducing the use of liquid fuel, improving the energy efficiency of the internal combustion engine and reducing the toxicity of their exhaust gases in a large city due to partial addition of hydrogen to the gasoline mixture. Thus, in the mode of imitation of the urban driving cycle, energy consumption was reduced by 2.4–5.6%, while gasoline was replaced by 8–17%. The toxicity of exhaust gases under steady-state conditions in bench conditions was reduced by components from 17–96%).

2. Without making significant changes in the design of MV, it is possible to achieve a significant reduction in the mass of hydrogen supply and storage systems onboard the MV through the installation of an electrolyzer and its components (Figure 3).

At the same time, on vehicles with an electronic engine control unit, correction of ignition timing and injection angles is necessary for various engine operating modes.

   The absence of large tanks for storing hydrogen (hydroxy gas) significantly increases the safety of using MV.

3. Hydrogen production using an electrolyser on board a vehicle is an energy-consuming process (for a maximum electrolyser capacity of 1.0 l/min per 1.0 liter of engine swept-volume capacity, the power consumption is about 400 W of electrical energy with a current of about 30 A).

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