Prospects for using hydrogen on railway transport

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Abstract. The paper presents the results of a study on the prospects of using hydrogen in railway transport. Factors influencing the development of the hydrogen energy market in the world are considered. According to experts, the share of the Russian Federation may amount to 10-15% of the world market. At the same time, South-East Asia is an important focus area for Russia. This is due to the availability of available raw materials (Sakhalin) and the short delivery time of hydrogen to the main consumers (China, Japan). Three key areas are identified as prospective research and development of the “Research & Development” program: 1 – generation, 2 – storage and transportation, 3 – consumption (use). The paper considers the main ways of using hydrogen fuel on autonomous traction rolling stock. In accordance with the energy strategy of the Russian Railways holding for the future until 2030, the main energy-saving technical solutions and technologies are the creation of a new generation of energy-efficient rolling stock. This also includes partial substitution of diesel fuel with the development of hydrogen fuel cells and the use of advances in the field of hydrogen energy. Currently, the company is working on the creation of serial two-diesel, hybrid locomotives, as well as gas-turbine and gas-thermal locomotives powered by liquefied natural gas. However, in terms of energy and environmental characteristics, the most promising type of fuel is hydrogen. Engineering solutions for generating hydrogen on board of locomotive are presented, and experimental results are presented. The developed hydrogen-aluminum generator makes it possible to organize a new approach in the working process of transport power plants by automatically feeding the initial components (aluminum) to the chemical reaction zone, depending on the locomotive engine’s demand for hydrogen in various operating modes.

1. Introduction
According to a number of experts [1-3], hydrogen is a promising fuel of the future, which is able to occupy a niche that now belongs to oil and gas. At the same time, hydrogen is considered not only as a fuel, but also as a tool for decarbonizing the electric power industry. Hydrogen can be considered as a way to store the generated energy. The World’s leading countries and corporations have adopted programs for the development of hydrogen energy. The leadership in this issue belongs to Japan [4], which is planning to build a “hydrogen society of the future” and is already purchasing hydrogen. The hydrogen market is formed and developing. Suppliers of hydrogen are Norway and Australia [5, 6]. The leading players in the market are the developed countries of the World: USA, Germany, Great Britain. Russia is not far behind on this issue. NTI market (National technology initiative) “EnergyNet” uses hydrogen energy as the main bid [2-3]. Leading state corporations (Russian Railways, Gazprom, RusHydro, etc.) have identified hydrogen as the fuel of the future in their long-
term development programs. Transport, stationary power engineering of industrial enterprises and autonomous municipalities are identified as the key directions for the development of hydrogen energy. The Arctic is named as the main testing ground for the introduction of hydrogen energy in Russia.

Samara State University of Transport - is a branch transport university, a member of the Scientific and educational center “Engen Future” and carries out research in the field of hydrogen energy. A key area of research is the development of hydrogen as a fuel in railway transport. Below are the results of a study on the prospects for using hydrogen in railway transport.

2. Analysis of the hydrogen market

The development of the hydrogen energy market in the World is influenced by three main factors.

The environmental factor - is the growth of environmental requirements. Currently, the comparative analysis in universal units-tons of conventional fuel is not in favor of hydrogen fuel. The reasons for this are the relative availability of “dirty energy” - the production of energy from hydrocarbons. However, in the future, the “Paris agreement” [2] makes “dirty energy” expensive. So, after 2020, the carbon tax of only one company, JSC “Gazprom”, will amount to 1.6 billion $ / year, and after 2030 – 3.8 billion $ / year. The result will be an increase in demand for hydrogen energy.

The cost factor - is a reduction in the cost of hydrogen energy products. The result will be possible by increasing the availability of technologies at all stages of the life cycle of hydrogen energy: generation, storage, transportation, consumption and disposal.

The safety factor - is the improvement of technologies for generating, storing, transporting and consuming hydrogen. It is expected to reduce hydrogen fragility, increase the efficiency of safety systems for working with hydrogen and increase the efficiency of consumption systems.

Analysis of expert agencies and foresights [1-6] in the field of energy development shows that the market of hydrogen can reach 6 billion $ by 2025 and 35 billion $ by 2030 (figure 1).

![Figure 1. The market of hydrogen: a – 2025, b – 2030.](image-url)
According to experts, the share of the Russian Federation may amount to 10-15% of the world market. At the same time, South-East Asia is an important focus area for Russia. This is due to the availability of available raw materials (Sakhalin) and the short delivery time of hydrogen to the main consumers (China, Japan).

According to “EnergyNet”, the potential for hydrogen production for Russia based on non-released capacity reserves is: 256-430 thousand tons of hydrogen per year for the united energy system (UES) of the North-West, 393-700 thousand tons of hydrogen per year for the UES of Siberia and 198-341 thousand tons of hydrogen per year for the UES of the East [3].

3. Analysis of promising research areas

Three key areas can be identified as promising research and development of the “Research & Development” program: 1 – generation, 2 – storage and transportation, 3 – consumption (use).

The first direction includes the creation of various main and auxiliary systems for generating hydrogen: conversion of methane and natural gas (reforming of hydrocarbons), water electrolysis, pyrolysis of hydrocarbons (including methane cracking). This direction also includes various systems for purifying the resulting hydrogen-membrane technologies.

The second direction includes the development of various hydrogen storage systems. The most promising method is storage of hydrogen in the adsorbed state. The barrier to overcome is to solve the problem of “hydrogen fragility” - the negative impact of hydrogen on metals. Of interest is the safe storage of hydrogen in LOHC (Liquid Organic Hydrogen Carrier) systems-they are able to attach and release hydrogen molecules if desired. This direction also includes the development of technologies for transporting hydrogen: by means of vehicles and pipelines.

The third direction includes stationary power engineering and vehicles. The most promising area of research is transport: road and rail transport. The object of this research is an electrochemical generator – fuel elements of rolling stock.

Table 1 shows the results of calculating the comparison of different types of fuel and hydrogen. The “hydrogen” position is calculated taking into account the methane cracking technology.

| Type of fuel    | Production and delivery to the consumer (TOE-Ton of oil equivalent) |
|-----------------|---------------------------------------------------------------------|
| Electricity     | 40 650.41 rubles/TOE                                                |
| Gas (CNG)       | 12 998.27 rubles/TOE                                                |
| Gas (LNG)       | 19 064.12 rubles/TOE                                                |
| Diesel          | 27 586.21 rubles/TOE                                                |
| Gasoline        | 26 845.64 rubles/TOE                                                |
| Hydrogen        | 9 548.08 rubles/TOE                                                 |

4. Use of hydrogen on railway rolling stock

Currently, “Russian Railways” company, as the largest customer of rolling stock, has formulated requirements for manufacturers to use energy-saving technological solutions and structural materials in the production and development of new types of locomotives and motor-car rolling stock. Work is underway to create serial two diesel, hybrid locomotives, as well as gas-turbine and gas-thermal locomotives that run on liquefied natural gas. However, in terms of energy and environmental characteristics, the most promising type of fuel is hydrogen.

In the short term (until 2025) JSC “Russian Railways” has outlined a program for the creation and implementation of locomotives on hydrogen fuel, in the number of: shunting locomotives: from 10 to 100 units per year; mainline locomotives: from 25 to 200 pieces per year.
In particular, companies JSC “Russian Railways”, together with JSC “Transmashholding” and “Rosatom”, are already working on creating a fuel-cell locomotive for use in the Sakhalin region of the far Eastern railway. The goal is to put this locomotive into operation by the end of 2021 and use it in suburban traffic instead of the PA-3 rail bus.

There are three fundamentally different approaches to using hydrogen fuel on autonomous traction rolling stock:

1. Use of hydrogen as an additive (1-60%) to carbon-containing fuel (diesel fuel or methane) in the working process of a diesel engine.
2. Complete conversion of the diesel engine to hydrogen fuel.
3. Using fuel cells as the locomotive’s power plant.

It should be noted that the use of hydrogen additives to traditional fuel can be considered an intermediate stage on the way to the complete conversion of diesel rolling stock to hydrogen.

At the Department “Locomotives” of the Samara State University of Transport (SSUT), experiments were conducted to study the characteristics of a diesel engine running on diesel fuel with the addition of hydrogen. The D-242 diesel with direct fuel injection was chosen as the object of research. Hydrogen with a purity of 99.9999 % was used as an additive. The hydrogen was supplied at a pressure of 0.1-0.4 MPa. The hydrogen consumption was maintained using an automated fuel control and supply system, the main element of which is the electronic gas flow controller Bronkhost EL-FLOW. Readings of the flow rate and supply of hydrogen were recorded in real time behind the screen of a personal computer monitor from the operator’s place. When conducting experimental studies of the D-242 diesel engine when hydrogen is supplied to the air receiver, measurements of the main parameters were performed at idle and load modes corresponding to the generator current of 15 A, 30 A and 45 A. To compare the results of diesel operation, the experiments were carried out alternately - on diesel fuel and with the addition of hydrogen.

The studies of the influence of hydrogen additives in the working process of diesel engines were mainly determined by the study of the behavior of such basic environmental parameters as CO, CO$_2$, NO$_x$, as well as the smoke content of exhaust gases.

As can be seen from figure 2, CO emissions with the supply of hydrogen tend to decrease under the steady-state diesel mode. Their content in the exhaust gases with the supply of hydrogen to the air receiver has become on average 2 times less.

The dependence of emissions of carbon dioxide CO$_2$ from the load without supply of hydrogen and supplying hydrogen (figure 3) showed that feed hydrogen content of carbon dioxide CO$_2$ in the exhaust gas increased on average by 4-8%.

Emissions of nitrogen oxides NO$_x$ with the supply of hydrogen in all engine operating modes (figure 4) decreased compared to emissions of nitrogen oxides NO$_x$ without the supply of hydrogen. The average decrease was 2-4 % [8].

![Figure 2](image_url)

**Figure 2.** Dependence of carbon oxide CO emission levels on load (generator current Ig, A) diesel D-242 with and without hydrogen supply.
Figure 3. Dependence of carbon dioxide CO$_2$ emission levels on load (generator current Ig, A) diesel D-242 with and without hydrogen supply.

Figure 4. Dependence of nitrogen oxide NO$_x$ emission levels on load (generator current Ig, A) diesel D-242 with and without hydrogen supply.

Measurement of smoke content when the diesel engine is running at idle and under load with the supply of hydrogen (figure 5) showed a tendency to decrease this parameter by 4-8 %.

Figure 5. Dependence of the smoke content N on the load (generator current Ig, A) diesel D-242 with and without supply of hydrogen.

The obtained dependences of concentrations of harmful substances CO, NO$_x$, CO$_2$ and smoke content in diesel exhaust gases confirmed the feasibility of using hydrogen in terms of its positive impact on the environment when used as a fuel.

Also, the test results showed that when adding hydrogen to the air receiver from 0.5% up to 3%, the consumption of diesel fuel decreased by 1.52–9.27 %. Moreover, the greatest effect was observed when the diesel engine was running at idle.
Based on the application of the similarity criterion of technical systems, it can be assumed that the effect of using hydrogen additives on a large-size diesel locomotive will be similar, which indicates the prospects for carrying out work in this direction. However, creating an engine that runs on hydrogen (both with additives and pure hydrogen) is accompanied by a number of technical difficulties. For example, it is necessary to create a safe hydrogen storage system on board of the locomotive; there are difficulties in preserving the resource characteristics of parts of the cylinder-piston group and the crank mechanism of the diesel engine; there are additional questions about creating a new system for regulating the supply of hydrogen fuel, etc.

Based on the above, the nearest prospect of using hydrogen fuel on autonomous traction rolling stock is the application of the 3<sup>rd</sup> approach - replacing the diesel power plant of the locomotive with fuel cells. The only problem that hinders the mass production of fuel-cell locomotives is that there are currently no enterprises in Russia that can create a fuel cell with a capacity of 1000-4000 kW. Therefore, the first priority is to test this technology on low-power industrial and shunting locomotives with a capacity of up to 700 kW.

As we know, there are certain differences in the conditions and specifics of operation of industrial and shunting locomotives from mainline ones, which is explained by their low speeds, frequency of train mass changes, constant reversing and an increased number of switches of the driver’s controller. All this and some other factors directly affect the modes of the diesel generator unit during the operation of the locomotive.

Shunting is an integral part of the transportation process. It employs approximately 45 % of the operating locomotive fleet, and its maintenance costs account for more than 25 % of total operating costs.

For example, according to the locomotive maintenance depot of Yershov, the Volga railway, diesel fuel consumption for shunting traffic in 2019 is significantly higher than fuel consumption for other types of traffic (figure 6).

![Figure 6. Diesel fuel consumption by locomotives by traffic types for 2019 according to the Yershov depot.](image)

In general, according to the shunting operation of locomotives, the following can be noted: the realized power is 20÷50 % of the nominal, idling is 40-73 % of the total operating time, including in the run-out mode from 8 to 10 %, and in the warm-up mode up to 3 %.

The main advantage of using fuel cells in comparison with a traditional engine is a higher efficiency, since there is no loss of energy conversion (chemical → thermal → mechanical → electrical). The fuel cell immediately generates electrical energy, bypassing the phase of mechanical energy. The resulting electricity can be immediately used to pull the locomotive by means of electric motors.
An example of the equipment layout of a shunting locomotive with a fuel-cell power plant is made for the crew part of a ChME3 locomotive, which is the most common shunting locomotive on the Russian railway network (figure 7).

![Figure 7. Layout of the shunting locomotive equipment with a fuel-cell power plant.](image)

As can be seen from figure 7, dismantling the diesel locomotive will allow the released huge part of the space to fill with fuel cells. Taking into account the numerical values of internal combustion engine volume (12.876 m$^3$) and fuel cells (1.004 m$^3$), we can assume that for conversion into shunting locomotives, fuel cells in the amount of 12 units are needed, which can be freely placed in the space of a dismantled diesel. The generated power of the autonomous section will be 676 kW, and the service weight will be reduced by 1.752 tons. It should also be added that full operation of the locomotive is possible with the use of five spare fuel cells [7].

The ability to change the number of series and parallel fuel cells installed on such a locomotive allows changing the output voltage without loss of power, which ensures smooth adjustment of the locomotive’s speed characteristics, without reducing its traction characteristics.

5. Engineering solutions

The comparative analysis of methods and ways for obtaining hydrogen has shown that the most suitable solution for on-board hydrogen production is aluminum hydrolysis, which consists in the interaction of aluminum with aqueous solutions of strong alkalis [10]. This method is compact and does not require much energy, and, therefore, is more acceptable for use as onboard sources of hydrogen for supplying locomotives power plants. In addition, the interest shown in this method is explained by its simplicity, efficiency and cheapness of the energy substances used in the reaction. Obtaining hydrogen directly on board of the locomotive in this way will solve the main problem – the safe operation of autonomous traction rolling stock using hydrogen fuel as an energy carrier without the possibility of storing it on board.

The hydrolysis reaction is described by the equation:

$$2\text{Al} + 2\text{NaOH} + 2\text{H}_2\text{O} \rightarrow 2\text{NaAlO}_2 + 3\text{H}_2[1]$$

The process of hydrolysis of aluminum is exothermic and actively proceeds at temperatures below 100°C. At the same time, if there is a sufficient amount of alkali in the initial solution, the reaction products are also liquid (a solution of sodium aluminate in an alkaline medium). The absence of insoluble reaction products makes this method of producing hydrogen preferable for autonomous power plants with a long service life. In addition, the positive advantage of the method is that the reaction (1) releases all the hydrogen contained in the initial components.

The great advantage of using hydrogen in the working process of diesel locomotives in this way is that it is not possible to radically change the design and parameters of their fuel systems, which makes it possible to install on the locomotive the necessary technical means for supplying hydrogen to the internal combustion engine, without additional costs for re-equipment of the locomotive as a whole.
There are several ways to improve the efficiency of diesel locomotives by using hydrogen fuel as an energy carrier:

1. The use of hydrogen as an additive to diesel fuel;
2. Saturation (enrichment) of diesel fuel with hydrogen.

For the implementation of on-board hydrogen production method of hydrolysis, the high-tech device for producing hydrogen are needed. These devices include hydrogen-aluminum generators.

When designing on-board hydrogen-aluminum generators, special attention should be paid to the development of their chemical reactor. The main requirements for hydrogen-aluminum generators are:

- maximum productivity and intensity of work;
- high yield and the greatest selectivity of the process;
- minimum energy costs for mixing and transporting materials through the reactor, as well as the best use of the heat of exothermic reactions or heat supplied to the reactor to heat the reactants up to optimal temperatures;
- easy handling and safety of operation, which depends on the design of the reactor and the presence of small fluctuations of the parameters of the process mode, which makes it easy to automate the operation of the reactor;
- low cost of reactor manufacturing and repair (simplicity of construction with the use of cheap structural materials);
- stability of operation with significant changes in the main parameters of the hydrogen generator operating mode (concentration, temperature, pressure, etc.).

Taking into account these requirements, several design variants of hydrogen generators for transport power plants were developed, protected by security documents [9-12].

Figure 8 shows a diagram of the latest patented technical solution protected by RF patent No 180295 dated 08.06.2018 for IPC classes F02D19/08, F02M25/10, H01M8/06, C01B3/08 “Power plant with hydrogen-aluminum generator” [12].

Its essence is to optimize the operation of the locomotive’s power plant when working together with an aluminum-hydrogen generator. This effect is achieved by supplying hydrogen in various quantities through the use of a regulator - a hydrogen flow meter, and at idle speeds of the locomotive’s diesel engine, hydrogen is supplied to the air collector, and at load conditions, the diesel fuel is enriched with hydrogen using a mixer. In addition, in order to create a jet stream of aluminum particles along the entire working length of the reactor of the hydrogen-aluminum generator, under the influence of gravity and as a result of reducing the granules of the solid aluminum reagent at a certain stage of heterogeneous topochemical reaction passes, the cylindrical container of the generator reactor is horizontally placed from top to bottom with sieve-filters of various degrees of fineness and are located as they decrease. Thanks to the bunker with a stock of solid aluminum reagent, as well as the possibility of switching hydrogen-aluminum generator in a mode of minimum consumption of aluminum, by reducing the hydrogen output to the minimum value, savings of energy raw materials of aluminum are generated and supplied hydrogen during the whole process [11,12].

The tests carried out on the prototype of hydrogen-aluminum generator allowed establishing an acceptable temperature regime in the range of 60-70 °C, which ensures its optimal operation. The specific capacity in this temperature range was 8.95*10^-4 m³ (m²*s). The experimentally obtained hydrogen output was 0.98-1.03 l/g, which makes it possible to design hydrogen-aluminum generators for any performance.

The developed hydrogen-aluminum generator provides a mode of auto-stabilization of hydrogen consumption, consists of two main parts and is not difficult to manufacture, configure and adjust, as it has simple geometric shapes and uses well-known functional elements and nodes.
Figure 8. Principal diagram of aluminum-hydrogen generator working together with a diesel engine: diesel 1, air collector 2, air flow sensor 3, hydrogen-air mixture flow sensor 4, exhaust collector 5, cylindrical body of the hydrogen-aluminum generator 6, generator cover 7, bypass pipe 8, electro-controlled valve 9, bottom of the generator body 10, generator reactor 11, reactor cover 12, hydrogen delivery line 13, hydrogen pressure sensor 14, hydrogen temperature sensor 15, electro-controlled valves 16, 17, hydrogen storage 18, electro-controlled valves 19, 20, cylindrical container 21, sieve-filters 22, solid aluminum reagent 23, reactor cooling coil 24, cooling water inlet line to the reactor coil 25, electro-controlled valve 26, alkali water flow meter 27, water temperature sensor at the generator inlet 28, hot water outlet line from the reactor coil 29, electro-controlled valve 30, hot water temperature sensor from the reactor coil 31, sump 32, electro-controlled valve 33, drain tank 34, electro-controlled valve 35, diesel fuel injectors 36, diesel fuel pump unit 37, fuel consumption sensor 38, the level of an aqueous solution of alkali 39, temperature sensor of an aqueous solution of alkali 40, pressure sensor at the outlet of the hydrogen storage 41, controlled heating element in the cylindrical body of the generator 42, shut-off element of the reactor 43, cone base of the reactor 44, pre-sump pipe 45, conical holes of the pre-sump of the hydrogen-aluminum generator 46, tank with an aqueous solution of alkali 47, pumping pump of an aqueous solution of alkali 48, self-cleaning filters of the reactor 49, bunker with a solid reagent (aluminum) 50, screw dispenser 51, dispenser drive 52,
6. Experimental results

To study the effect of addition of hydrogen on the economic characteristics of a diesel shunting locomotive ChME3 No 4529, tests were carried out when it was running on diesel fuel, as well as with the addition of hydrogen supplied to the input of the air receiver in the conditions of the rheostat testing station and the environmental control point of the Samara locomotive depot.

Measurements of fuel pump slats from the position of the driver’s controller (figure 9) showed that the consumption of diesel fuel when adding hydrogen to the working process of the diesel engine decreases both when the positions are set and reset, as evidenced by a decrease in the output of the fuel high-pressure pump slats (figure 9).

As can be seen from the dependence of the diesel power on the output of the fuel pump slats (figure 10), when hydrogen is supplied, the output of the fuel high-pressure pump slats decreases and the greater the greater hydrogen consumption. The diesel power at the constant output of the fuel pump slats at the nominal mode increases by 3.3-3.8%, which corresponds to a decrease in the specific consumption of diesel fuel by the same amount. This shows the improvement of the combustion process in the cylinders of a diesel engine.
Figure 10. Power dependence on the output of the fuel pump slats of the ChME3 locomotive No 4529 with and without hydrogen supply (work under load).

7. Conclusions

The examined prospective use of hydrogen in rail transport, supported by experimental results allow considering the direction of technological development of rail transport as a priority in addressing the issue of reducing the environmental impact on the environment and reducing the costs of fuel and energy resources of JSC “Russian Railways”.

The current methods and methods for producing hydrogen are generally acceptable for implementing a centralized scheme for its use in transport, which involves storage methods using balloon or cryogenic systems. Of course, the use of hydrogen on locomotives in this form cannot be considered acceptable because of the technological complexity and increased danger.

The developed and proposed technical solutions allow using hydrogen as fuel on autonomous traction rolling stock on the principle of “using hydrogen without hydrogen on board”. This, in turn, will allow moving away from the use of onboard hydrogen storage systems, the operation of which is unsafe.

The use of onboard hydrogen-aluminum generators and fuel cells will solve the safety problem when using them on autonomous traction rolling stock.

The obtained experimental results give a strong reason to assert that the use of breakthrough hydrogen technologies will significantly improve the efficiency of traction rolling stock by reducing the environmental pressure on the environment.

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