ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

WORLD TRENDS IN THE DEVELOPMENT OF VEHICLES WITH ALTERNATIVE ENERGY SOURCES

Nguyen Khac Tuan[1], Kirill Evgenievich Karpukhin[2], Aleksey Stanislavovich Terenchenko[2] and Aleksey Fedorovich Kolbasov[2]
[1]Thai Nguyen University of Technology (TNUT), Street, Tich Luong Ward, Thai Nguyen City, Vietnam
[2]Central Scientific Research Automobile and Automotive Institute ("NAMI"), Ul Avtomotornaya, Moscow, Russia
E-Mail: n.tuan@bk.ru

ABSTRACT

Decreasing oil and gas reserves and increasing sensitivity of consumers to environmental protection force automotive industry to research possibilities of alternative technologies. Herewith, application of fuel cells in automobiles can not only make significant contribution to environmental protection, but also provide cardinal improvements of vehicle quality in general. This work discusses main trends of development of vehicles with alternative energy sources. World experience in development of electric and hybrid vehicles as well as hydrogen vehicles is analyzed. The main advantages and disadvantages of energy efficient and environmentally safe transport are reviewed. Main trends and aspects of development of promising infrastructure are classified and considered. World experience of development of various systems of accumulation and storage of electric energy is analyzed. Forecasts of development of vehicles using alternative energy sources are overviewed.

Keywords: vehicle, electric vehicle, hybrid vehicle, hydrogen vehicle, energy efficiency, hydrogen, fuel cells, charging stations, environmental regulations.

INTRODUCTION

Progress does not stand still, and once again environmentally safe and cost-efficient vehicles attract attention of researchers and developers [1]. However, analysis of already commercially implemented solutions in the field of reduction of harmful emissions and decrease in operation costs reveals that up till now there is no single solution and each company pursuits its own strategy.

Tesla Company, having started production of electric cars in 2007, promotes the concept of high-capacity cell and proposes Tesla charging stations for rapid charging with currents up to 70A, which enables cell charging more than by 50% in 30 minutes. Renault Company decided to relieve the car owners of responsibility for service fee. Thus, it became possible to develop strategy of rapid battery replacement at specialized automatic stations, where this procedure is performed in less than 5 minutes.

Marketing experts of BMW AG have proposed electric car with the option known as Range Extender [2], which is an on-board petrol generator producing energy for battery charging and without direct link with the wheels. However, according to the classification and in compliance with UN regulations, when a vehicle is equipped with two or more energy sources, it should be considered as hybrid or vehicle with integrated energy assembly (distributed hybrid) [3].

Toyota Corporation started development of hybrids based on parallel system of integrated energy assembly on the basis of petrol internal combustion engine (ICE) and electric engine: Toyota Prius, RAV4 EV. Peculiar features of these vehicles are ICE operating by the Atkinson cycle and system of electricity accumulation up to 4.5 kWh comprised of NiMH cells.

Which strategy of reduction of harmful emissions is the most promising?

RESEARCH METHODS

The study used research methods of system analysis, including methods of decomposition and optimization of technical solutions. Each of the selected parts is analyzed separately within a whole. Empirical method is applied, which is comprised of data acquisition, scientific analysis, generation of hypothesis and development of theory.

RESULTS AND DISCUSSIONS

It is known that an American researching company published data obtained by analysis of fuel consumption by existing hybrid vehicle with electric engine and compared them to gasoline analogs (Figure-1) [4]. Therefore, increase in price for components of electric transmission and accumulation system of electric energy can be reimbursed for numerous vehicles not earlier than after 160-180 thousand kilometers. However, BMW Active Hybrid 3 (F30) will not be able to return the investments into electric components even after 2 million kilometers.

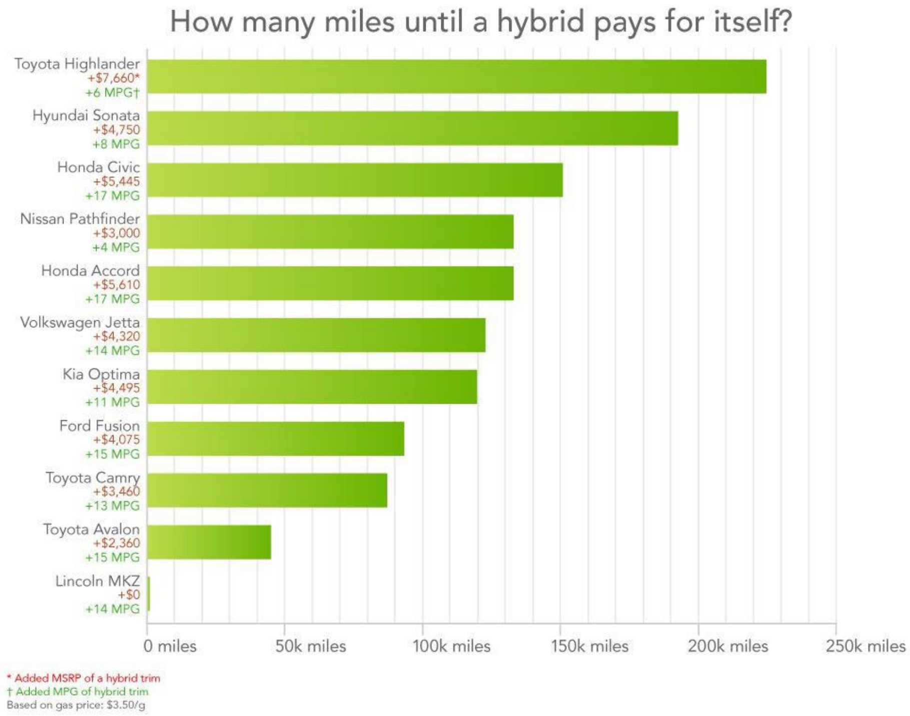

Figure-1. Miles required for hybrid to achieve repayment.

Another challenging and promising source of electric energy for vehicles is hydrogen. More than two hundred years ago a chemical generator was invented, where hydrogen was combined with oxygen and produced electric energy with water as byproduct. The principle of this generator is that membranes allow flow of protons and entrap electrons. Two electrodes on both sides of membrane, positive (anode) and negative (cathode), form electric circuit. Hydrogen is supplied from one side of membrane, and oxygen - from another side. Catalyst applied onto membrane activates splitting of hydrogen into proton and electron. Proton passes via membrane and produces water after combination with oxygen, and electron passes into electric circuit (Figure-2).

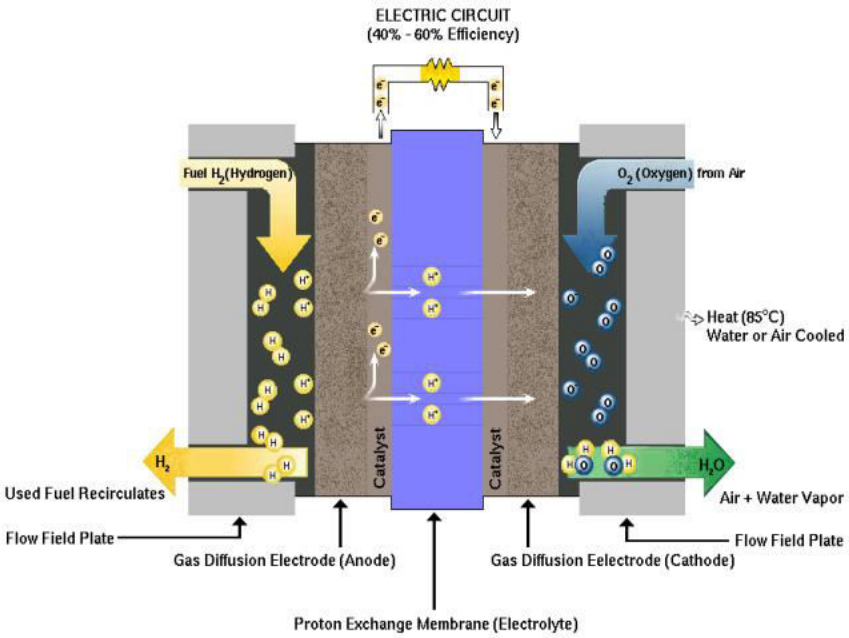

Figure-2. Schematic view of hydrogen fuel cell.

ARPN Journal of Engineering and Applied Sciences

Therefore, the first widely applied electric generators were hydrogen/oxygen fuel cells initially used on Russian and US space satellites.

Average voltage of hydrogen fuel cell is from 0.6 to 1.0 V, thus, a bench of fuel cells can provide any voltage except for the cases with restricted configuration space.

Development of innovative technologies or their commercial implementation is often related with the events of global scale, such as 2020 Summer Olympics, and in this regard the Government of Japan stimulated motor manufactures to create infrastructure for hydrogen vehicles and to start serial manufacture of revolutionary vehicle with a battery of hydrogen fuel cells and electric transmission. The Tokyo Metropolitan Government, responsible for erection of Olympic and Paralympic villages, allocated $367 million for development of hydrogen vehicles and charging stations in vicinity of sports facilities. "After closing of the Olympics, the village will become environmentally safe residential district with hydrogen system of new generation," mentioned Hikariko Ono, a spokesperson for the Tokyo Organizing Committee. In the Tokyo Olympic village hydrogen fuel cells will create integrated infrastructure: from buses and vehicles to building energy supply. Hydrogen will be supplied to the district via modern pipeline.

As for now it is known that Toyota Corporation started manufacture of serial vehicle with integrated energy assembly based on hydrogen fuel cells and electric engine: Toyota Mirai (Figure-3) [5].

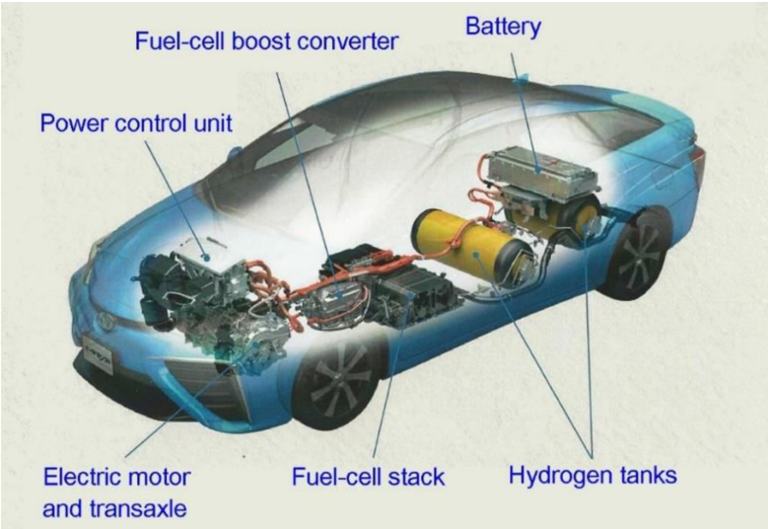

Figure-3. Toyota Mirai layout flowchart.

A vehicle should be charged only with hydrogen which, flowing via ion exchange membrane combines with ambient oxygen and produces electric energy and water vapor. Therefore, such vehicle does not generate harmful atmospheric emissions; water vapor is emitted form exhaust pipe instead of carbon monoxide. After 4-km test run the generated water amount was 240 milliliters. The hydrogen tank capacity is sufficient for about 650 km, its complete charging takes about three minutes.

Therefore, after traveling on a single charge the vehicle generates about 40 liters of water which should be analyzed separately including the disposal aspect, when fleet of such vehicles increases.

Toyota Mirai equipment is as follows: hybrid assembly on the basis of hydrogen fuel cells (FC stack, model FCA110) generates electric energy with efficiency of hydrogen conversion into electricity up to 83%. Maximum power of the assembly reaches 114 kW. The generated electric energy is then transmitted into accumulating and storing system in the form of nickel-metal hydride battery with maximum output power of 21 kW. Moreover, the accumulating and storing system obtains additional charge from regenerative braking. Maximum power of the electric engine is 113 kW or 154 hp. Control unit is comprised of invertor, which converts direct current into alternating current. Power unit controls output power of fuel cells according to adaptive algorithm depending on travelling manner. Two hydrogen tanks of 60 and 62.4 liters are installed in the bottom part of vehicle body. The gas in stored in balloons under pressure of 7 MPa [6]. Maximum distance covered on the basis of a single charge in JC08 mode (Japan method of measurement of fuel consumption) is 650 km. Herewith, the time of complete charging of two balloons is three minutes, that is, this vehicle is similar to conventional vehicles in terms of recovery of energy source. Maximum velocity of the vehicle is 175 km/h.

The Mirai market price in Japan is ¥7.23 million ($60.7 thousand), in addition, the Government subsides each domestic buyer in amount of $17 thousand. Moreover, the customer obtains 24 hour support on the roads and eight year warranty for fuel cells and electric drive.

While analyzing the main trends in the field of reduction of vehicle toxicity, it is possible to highlight three main roads of current development:

- electric cars;
- vehicles with integrated energy assembly (IEA) (ICE + electric engine);
- hydrogen vehicles.

Let us consider an electric car in its pure form without additional electricity generators. At present in order to provide 150 km run an electric car should be equipped with accumulating system comprised of a battery with Li-ion cells, converters, electronic auxiliaries and power drives, total weight of car is at least 350 kg. After consumption of accumulated electric energy, it is required to perform charging, which takes from 2 to 8 hours (depends of manufacturer of charging station) and capacities of electricity networks.

As mentioned previously, electric cars and vehicles with IEA were developed about one hundred and fifty years ago; however, accumulating systems for electric car are still expensive and cumbersome, when compared with conventional ICE systems.

The issue of environmental safety of autonomous electric vehicles cannot be considered without aspects of disposal of elements of accumulating system. The main components of existing accumulators are lithium, lead and electrolyte. Presently the issue of disposal or replacing of accumulating and storing cells with new ones is not still solved in some countries manufacturing electric cars.

For instance, while considering the challenges of development of electric cars and vehicles with IEA numerous bottlenecks were revealed, including car disposal in general [7]. As for now, many cars with integrated energy assembly consisting of ICE and electric engine are traded in Russia [8]: Toyota and Lexus (NiMH), BMW, Mercedes-Benz, VW (Li-ion), as well as two registered models of electric cars (Renault, Mitsubishi), but none of these companies announced a schedule of cell disposal in Russia, although Toyota has been in the Russian market already for more than seven years, and accumulating systems can require replacement. In winter the accumulating and storing batteries' energy is consumed for heating of passenger compartment, capacity decreases and driving distance can drop by 2 times, since an average electric car should be equipped with a 2-3kW heater [9]. Taking into consideration lighting and other necessary systems, the driving distance can decrease even by three times. In general, operation at low temperatures is possible, though, charging at the temperatures below 0°C is not recommended by manufacturers, that is, thermal regulation of battery is especially required [10].

Nevertheless, electric car, as exemplified by Rimac Concept_One, proved that among supercars it has no rivals in terms of dynamic properties compared with vehicles on the basis of conventional energy sources. Driving distance and dynamics of Tesla serial electric cars are at least the same as those in its category manufactured by BMW, Mercedes and others.

Another obstacle for wide scale implementation is the rate of energy recovery for electric car; this is another important issue, which prevents competition of electric car with ICE vehicle. However, contrary to filling stations, location of charging stations has no strict limitations and can be located in more convenient places, for instance, at parking lots near supermarkets, underground parking of apartment blocks, at municipal parking lots and so on. At present systems of rapid replacement of drive battery are not common. Tesla Company installs high capacity charging stations: Supercharger, which charges drive battery up to 80% in 30 min, provided that vehicle is equipped with special unit. It is known that the use of such charging devices is not free of charge from January 1, 2017 for new owners of Tesla vehicles. The reserve of 400 kW will be allocated for new customers at Supercharger stations, which in terms of kilometers does not exceed 2500 [11].

The use of high capacity charging stations not only affects resources of drive battery, but also creates difficulties in supply of such power to charging stations as well as its distribution.

With increased fleet of electric cars and simultaneous charging there will be drops and overloads in electric networks. In order to solve this problem, smart charging system (Vehicle-2-Grid) is being developed; it should equalize consumption and decrease the risk of emergencies [12].

Power generated by electric plants of the world is significantly lower than power of all modern vehicles. The generated electric power is insufficient for charging of many electric cars.

Taking into consideration low driving distance of most electric cars at a single charge, we obtain high load on electric networks in general, which require global retrofitting.

The following car categories with integrated energy assemblies should avoid some disadvantages of the electric car, mentioned above, though, they have their own disadvantages.

Firstly, we should exactly define which vehicle can be considered as a hybrid or a vehicle with integrated energy assembly. Item 2.21 of the Russian Standard GOST P 41.83-2004 (UN/ECE Regulation No. 83) defines it as follows:

"Hybrid vehicle (HV)" means a vehicle with at least two different energy converters and two different energy storage systems (on vehicle) for the purpose of vehicle propulsion.

According to these definitions, HV is most often met in the form of internal combustion engine (ICE) and electric engine, which prevents operation of ICE in inefficient modes and provides regeneration of kinetic energy aiming at charging of drive battery. Therefore, fuel efficiency of power unit increases.

Such vehicles are characterized by certain advantages and disadvantages in comparison with electric cars.

The following can be considered as disadvantages:

- More complicated design in comparison both to electric cars and to conventional cars with ICE.

ARPN Journal of Engineering and Applied Sciences

- Higher amount of mechanical elements in comparison with electric car. Operation costs are the same as those of conventional car with ICE, which respectively results both in lower reliability and maintenance costs related with repair expenses.
- Higher environmental pollution in comparison with electric car.
- Necessity in conventional fuel.
- Higher consumptions per 1 km in mixed or suburban cycle.
- Onboard electronics controlling power unit is based on more complicated algorithms, since it should optimally synchronize power unit operation.
- Existence of multistage transmission, which also decreases total efficiency of integrated energy assembly.
- Upon operation at lower temperatures, due to partial load modes of accumulators the driving distance with electric drive can decrease significantly as a consequence of low heating of accumulators.

One type of electric HV should be mentioned individually - PHEV or Plug-In-Hybrid. This HV variant is equipped with relatively more powerful electric engines, the accumulator capacity is higher in comparison with conventional hybrid vehicle with electric engine, that is, driving distance using electric drive was increased. The main advantage of this variant is that the PHEV can be charged from electric mains. Therefore, for moderate distances (as a rule, up to 20 km) operation of ICE is not required.

One more advanced solution in the field of improvement of energy efficiency and power loading of electric cars and HV is installation of photoelectric converters on the car roof [13]. The first serial vehicle manufactured by Toyota Motor Corporation is Toyota Prius (Figure 4).

Figure-4. Toyota Prius with photoelectric converters.

According to the expert opinion of Toyota Motor Corporation, this option will provide 10% increase in driving distance on a single charge and make it possible to charge HV cell during parking.

Vehicles using hydrogen as fuel

Numerous works are devoted to the use of hydrogen as fuel. The main concepts of these works were separated into two branches:

a) The use of hydrogen as fuel for ICE.
b) The use of stack of hydrogen fuel cells with electric chemical generator producing hydrogen or directly with tanks for hydrogen storage.

The first approach has been used by engineers of BMW AG for a long time.

BMW Hydrogen 7 is a bi-fuel (petrol/liquid hydrogen) vehicle developed in the scope of Clean Energy project, which planned to manufacture and sell 100 vehicles. It was completed to May, 2007. In March, 2008 total driving distance of these vehicles all over the world was more than 2 million kilometers. However, operation of such vehicles requires for special charging station and increased safety requirements, since hydrogen is stored in liquid form at the temperature not higher than -253°C, hence, the relevant activities were terminated.

Another variant is related with fuel cells. Hydrogen fuel cells generate electric energy, which is accumulated in accumulating and storing system and then transferred to vehicle power drive, thus replacing internal combustion engine.

The main advantages of fuel cell installed into vehicles are high efficiency in comparison with ICE. The efficiency of modern internal combustion engine reaches 35%, and the efficiency of hydrogen fuel cell is 45% and even higher.

According to tests performed by Ballard Power Systems, the efficiency of hydrogen fuel cells installed on a bus reached 57%.

As a rule, vehicles and buses are equipped with proton exchange membrane fuel cells (PEM); their main advantages are as follows: portability, low weight, low temperature of reaction. However, the hydrogen fuel cells, as any other power source, are characterized both by their pros and cons. It is believed that the main advantage of hydrogen vehicle is its environmental safety. It is generally accepted that hydrogen combustion generates water instead of carbon monoxide, to be more exact: water vapor. However, air containing nitrogen is used instead of pure oxygen. As a consequence, nitrogen oxides are generated in combustion chamber. And their impact on environment can be even worse than that of common exhaust gases.

Moreover, high quality hydrogen is sufficiently expensive product, and it should be delivered to charging station, it is necessary to store it and to perform charging of vehicles.

There are several methods of hydrogen production:

a) On the basis of natural gas. It is based on conversion of methane with water vapor. Final product is a mixture, which is known as synthesis gas. The process conditions: nickel catalyst and 1000°C. However, gas is a good energy carrier itself, it is unreasonable to additionally process for subsequent combustion, it is possible to combust methane without extra charges;

b) On the basis of water. Transmission of water vapor above glowing coke (T = 1000°C). In order to obtain one cubic meter of hydrogen four-fold electric energy is consumed than generated upon combustion of this amount;
c) Decomposition of oil products, thus again considering non-renewable natural resources;
d) Electrolysis of aqueous solutions of salts (*NaCl*).

It should be taken into account that hydrogen production is related with harmful emissions, and it is unknown at starting stage whether it is efficient to use hydrogen for vehicles in high amounts. Instead of emission of exhaust gases, the wastes will be accumulated accompanying gas generation.

In addition, the issue of storage is very problematic. Presently it is not solved, hydrogen can penetrate through any material, it is required to store it in liquid form which involves additional sufficiently high expenses, which should be added to those incurred at production stage. Gas leakage results in generation of explosive mixture with air.

In general there is a hazard of hydrogen application as fuel, and it is related with two factors: high hydrogen volatility due to which it penetrates through very small gaps, and ease of ignition. Hydrogen is more dangerous than petrol, since it burns in mixture with air in wider range of concentrations. Petrol does not ignite at λ lower than 0.5 and higher than 2, and hydrogen at such ratios is flammable and explosive. Hydrogen, stored in tanks under high pressure, in the case of tank breakage evaporates very quickly, which is a positive point. In addition, in order to use hydrogen, it necessary to account for its volatility, which makes the storage more complicated.

In order to use it on vehicles, hydrogen storage systems are developed, which should provide safety and integrity of the fuel: tanks with multilayer walls made of special materials. However, implementation of such expensive system on vehicles increases the operational costs.

While considering hydrogen vehicles, the project of nanoFlowcell AG should be mentioned (Figure-5), where flow cells are used, and it is a new trend in development of environmentally safe transport [14].

Figure-5. Quant e-sport limousine with nano flowcell drive.

Technical capabilities of this vehicle are excessive: torque - 2900 Nm, accelerating to 100 km/h, according to calculations, is 2.8 s, maximum speed can reach 380 km/h. Driving distance of this electric car is in the range of 400-600 km on a single charge. Such driving distance is provided by flow cells, their operation principle is illustrated in Figure-6.

ARPN Journal of Engineering and Applied Sciences

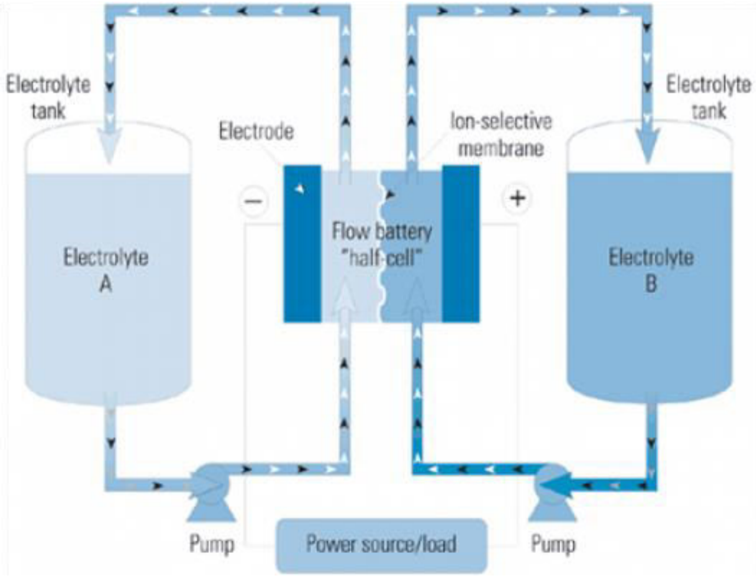

Figure-6. Operation principle of flow cells.

Technology of flow cells originates in spacecraft industry: for the first time such energy source was patented by NASA in 1976 and was intended for power supply of spacecraft. It combines engineering principles and advantages of conventional accumulators, fuel cells and even internal combustion engines.

Flow cell is recharged by replenishment of liquids required for the reaction. In addition, it was found that such batteries have no memory effect; they retain their capacity over the years, since it depends on capacity of tank with reagents and the power depends on sizes of reactor.

Obvious approach to power increase of fuel cell is increase in electrode surface area. However, the novelty of this approach is essentially in the electroactive fluids, into which more active substances were introduced using nanotechnologies. In addition to electroactive substances, the fluid contains crystalline nanoparticles, which can form spatial structures in direct vicinity of electrodes. As a consequence, the charge is generated not only on electrode surface, but in the adjacent space in the fluid. The space where reaction occurs is by far higher than usual. The composition is not disclosed.

CONCLUSIONS

Modern vehicles are characterized by high cost efficiency, environmental safety and, as a consequence, energy efficiency. However, full extent of these properties can be manifested only upon uniform motion, even in relatively wide range of speeds and loads. Herewith, conditions for longtime motion at constant speed exist only on suburban roads or highways. Upon urban traffic, characterized by constant alteration of phases of acceleration, short uniform motion, deceleration and halting with idle running engine (traffic light, pedestrian crossing, or in jamming), upon motion at moderate speeds fuel consuming and environmental properties of standard vehicles impair significantly. Several reasons exist: insufficient use of potential engine power upon motion with limited speed under city conditions, when engine operates with increased specific consumption; constant efforts aimed at accumulation of kinetic energy by vehicle, which subsequently in short time is converted into heat and lost upon working deceleration of vehicle; energy waste upon idle running engine.

Solution of these problems is in development of electric vehicles; their wide-scale manufacture is under way in leading countries of the World as evidenced by this work. Development of electric vehicles will allow to avoid environmental disaster, which approaches humanity as a consequence of increase in toxic emissions of various vehicles consuming engine oils, and to solve some problems related with fuel saving.

Currently all car manufacturers are involved in development of energy efficient and environmentally safe vehicles. There is neither single solution nor trend in the developments, which is favorable for different approaches, generating numerous both positive and negative opinions. The greatest problem for implementation of vehicles using alternative fuel sources is the absence of infrastructure or its insufficient development. This issue relates both to pure electric car and vehicle with integrated energy assembly including a stack of hydrogen fuel cells and driving electric transmission. Radically new fuel types will also require for dedicated infrastructure and sufficient time for its development, meanwhile, more challenging energy sources for vehicles could be developed.

REFERENCES

[1] Mirzoev G. and A. Kazarov. 2010. Development of electric cars at OAO AVTOVAZ. pp. 18-25.

[2] Jeong J., W. Lee, N. Kim and K. Stutenberg. 2017. Control Analysis and Model Validation for BMW i3

Range Extender. SAE Technical Paper 2017-01-1152, doi: 10.4271/2017-01-1152.

[3] Kulikov I., A. Shorin, S. Bakhmutov, A. Terenchenko and K. Karpukhin. 2016. A Method of Powertrain's Components Sizing for a Range Extended Electric Vehicle. SAE Technical Paper 2016-01-8096, doi: 10.4271/2016-01-8096.

[4] Are Hybrid Cars Really Worth the Extra Cost? Date view 10.04.2017 http://www.cheatsheet.com/automobiles/are-hybrid-cars-really-worth-the-extra-cost.html/?a=viewall.

[5] Hasegawa T., H. Imanishi, M. Nada and Y. Ikogi. 2016. Development of the Fuel Cell System in the Mirai FCV. SAE Technical Paper 2016-01-1185, doi: 10.4271/2016-01-1185.

[6] Yamashita A., M. Kondo, S. Goto and N. Ogami. 2015. Development of High-Pressure Hydrogen Storage System for the Toyota “Mirai”. SAE Technical Paper 2015-01-1169, doi: 10.4271/2015-01-1169.

[7] Kolbasov A. 2012. In Proceedings: Modern materials, equipment and engineering. 2-nd International Workshop. pp. 139-141.

[8] Rakov V. 2013. Razvitie parka gibridnykh avtomobilei (Development of fleet of hybrid vehicles). Mir transp. (1): 52-59.

[9] Karpukhin K. and A. Terenchenko. 2016. Features of Creation and Operation of Electric and Hybrid Vehicles in Countries with Difficult Climatic Conditions, for Example, in the Russian Federation. IOP Conference Series: Materials Science and Engineering 157 012014, pp. 1-7.

[10] Shorin A., K. Karpukhin, A. Terenchenko, S. Bakhmutov and R. Kurmaev 2015. Temperature control of the battery for hybrid or electric vehicle. Biosciences Biotechnology Research Asia. 12(2): 1297-1301.

[11] Charging Estimator. Date views/ 14.05.2017 https://www.tesla.com/charging.

[12] Shinzaki S., H. Sadano, Y. Maruyama and W. Kempton. 2015. Deployment of Vehicle-to-Grid Technology and Related Issues. SAE Technical Paper 2015-01-0306, doi: 10.4271/2015-01-0306.

[13] Urabe S., K. Kimura, Y. Kudo and A. Sato. 2016. Effectiveness and Issues of Automotive Electric Power Generating System Using Solar Modules. SAE Technical Paper 2016-01-1266, doi: 10.4271/2016-01-1266.

[14] Bi-ION - Energy of the Future. Date views 16.05.2017 http://emagazine.nanoflowcell.com/technology/bi-ion-energy-of-the-future/.